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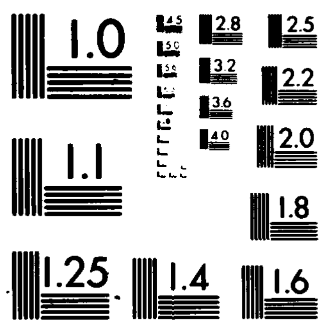

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PAVEMENT EVALUATION AND OVERLAY DESIGN USING VIBRATORY NONDESTRUCTIVE TESTING AND LAYERED ELASTIC THEORY

Volume II

Validation of Procedure

Richard A. Weiss and Jim W. Hall, Jr.

U. S. Army Engineer Waterways Experiment Station
Geotechnical Laboratory
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MAY 1980
FINAL REPORT

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16. Abstract

A method of pavement evaluation and overlay design based on vibratory nondestructive testing and layered elastic theory was developed in Volume I of this report. Volume II validates this method by comparing it with the conventional methods of evaluation and overlay design for rigid and flexible pavements. Three airport sites were used for the validation. Results of the validation showed good agreement between allowable loads determined from the NDT-elastic theory method and the conventional standard method. However, there was poor agreement between overlay thickness requirements determined from the two methods.

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PREFACE

This study was conducted during the period October 1977 to December 1978 by personnel of the Geotechnical Laboratory (GL), U. S. Army Engineer Waterways Experiment Station (WES), for the U. S. Department of Transportation, Federal Aviation Administration, as a part of Inter-Agency Agreement No. DOT FA73WAI-377, "New Pavement Design Methodology."

The study was conducted under the general supervision of Messrs. J. P. Sale and R. G. Ahlvin, Chief and Assistant Chief, respectively, of GL; R. L. Hutchinson and H. H. Ulery, Jr., Chief and Principal Technical Advisor, respectively, of the Pavement Systems Division; and under the direct supervision of Messrs. A. H. Joseph, Chief of the Engineering Investigation Testing and Validation Group; and J. W. Hall, Jr., Chief of the Prototype Testing and Evaluation Unit. The programming for this study was accomplished in part by Mr. Ricky Austin, Research and Analysis Group. Significant contributions were made by Mr. A. J. Bush III of the Prototype Testing and Evaluation Unit, and by Dr. W. R. Barker of the Research and Analysis Group. The report was written by Dr. R. A. Weiss and Mr. J. W. Hall, Jr.

COL John L. Cannon, CE, and COL Nelson P. Conover, CE, were Directors of the WES during the conduct of this study and the preparation of this report. The Technical Director was Mr. F. R. Brown.

METRIC CONVERSION FACTORS

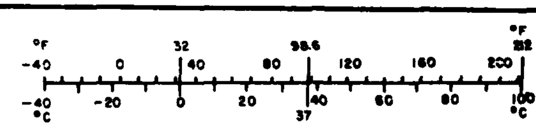
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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INTRODUCTION

BACKGROUND

The increasing expense of pavement construction and rehabilitation makes it essential to have a fast and reliable method of accurately predicting the allowable load-carrying capacity and the required overlay thickness for pavement upgrading. The method of vibratory nondestructive testing of pavements can play an important part for the rapid evaluation of airport pavements.[1-6] The U. S. Army Engineer Waterways Experiment Station (WES) was requested by the Federal Aviation Administration (FAA) to develop a method of pavement evaluation and overlay design based on vibratory nondestructive testing combined with a layered elastic theoretical formalism.[7] This report evaluates this method of pavement evaluation and overlay design.

The method of pavement evaluation and overlay design validation presented herein consists of determining the subgrade Young's modulus from the dynamic response of a pavement measured by vibratory nondestructive tests and using the layered elastic theory and the determined value of the subgrade Young's modulus to calculate the allowable load-carrying capacity and the required overlay thickness of a pavement.

Two computer programs, SUBE and PAVEVAL, are used to evaluate a pavement based on vibratory nondestructive testing and layered elastic theory. The computer program SUBE calculates the value of the subgrade Young's modulus from vibratory nondestructive field test data, and the computer program PAVEVAL calculates the allowable load-carrying capacity and the required overlay thickness for pavement upgrading.

This study compares the pavement evaluation and overlay design method that uses vibratory nondestructive testing and layered elasticity theory with the conventional method for evaluating asphaltic concrete (AC) pavements that uses the California Bearing Ratio (CBR) and with the Westergaard method of evaluating portland cement concrete (PCC) pavements.[8]

The CBR and Westergaard methods required destructive tests to measure the CBR and coefficient of subgrade reaction, respectively. To circumvent the destructive tests, a vibratory nondestructive test method of evaluating AC and PCC pavements was developed at the WES, which directly correlates the allowable load-carrying capacity and required overlay thickness to a dynamic stiffness modulus (DSM) that is measured at the pavement surface. The combined layered elastic theory and vibratory nondestructive test methods of pavement evaluation are also compared with the direct DSM correlation method.

The DSM is obtained from vibratory nondestructive test data that are obtained using the WES electrohydraulic vibrator, which can generate dynamic loads up to 15 kips (peak value) with a constant 16-kip static load (WES 16-kip vibrator) and a constant frequency of 15 Hz.[4] These data consist of dynamic load-deflection curves that are measured at the pavement surface. The dynamic load-deflection curves are nonlinear in general, and the DSM is the slope of the dynamic load-deflection curve for a dynamic load of about 10-14 kips. The measured DSM is corrected to a common pavement temperature of 70°F, and the corrected value of the DSM is correlated to the allowable load-carrying capacity and the required overlay thickness of a pavement.[1,6] The DSM method is empirical and does not take into consideration: (a) the layered elastic structure of the pavement, (b) the interface conditions between the pavement layers, and (c) the load transfer across rigid pavement slabs.

In order to improve on the method of directly correlating pavement performance with vibratory nondestructive test data, an attempt was made to combine the layered elastic theory of pavements with the pavement impedance values measured by vibratory nondestructive testing. In this way, the pavement structure could be considered. The layered elastic model of pavements required the Young's modulus and Poisson's ratio of the subgrade and pavement layers to be known. The elastic moduli of the pavement layers are estimated by various means, and only the subgrade Young's modulus is obtained from vibratory nondestructive test data.

Three airport pavement sites were selected for this validation, Albuquerque Sunport, Minneapolis-St. Paul International Airport, and Knox County Airport (Rockland, Maine). Vibratory nondestructive tests and conventional destructive tests were conducted at these pavement sites. Pavement properties, such as thicknesses, moisture content, density, and CBR, were determined by drilling holes through the pavement layers and the subgrade. Undisturbed subgrade soil specimens were taken for laboratory resilient modulus tests. Samples of the AC, PCC, base, and subbase were also obtained for laboratory analysis.

OBJECTIVES

The results of the combined methods of layered elastic and vibratory nondestructive testing are compared with the conventional methods of pavement evaluation and overlay design. The specific objectives of this study are:

a. To compare the values of the subgrade Young's modulus predicted from vibratory nondestructive tests by SUBE with the subgrade Young's modulus values obtained from measured CBR values using the relation $E = 1500$ CBR, and with Young's modulus values obtained from laboratory resilient modulus tests.

b. To compare the values of the allowable load-carrying capacity and the required overlay thickness calculated by the layered elastic theory and the vibratory nondestructive testing approach with the conventional destructive CBR and Westergaard methods and also with the direct correlation DSM method.

SCOPE

To achieve these objectives the following experimental work and analyses were conducted:

EXPERIMENTAL WORK

a. Vibratory nondestructive tests were conducted to obtain dynamic load-deflection curves for AC and PCC pavements at three airport pavement sites.

b. CBR values were measured for the base, subbase, and subgrade of the pavements at the three airport sites.

c. Laboratory resilient modulus tests were conducted on undisturbed soil samples taken from the subgrade at several locations at the three selected airport sites.

d. Laboratory soil tests were conducted on samples of base, subbase, and subgrade materials to determine their classification.

ANALYSES

a. The computer program SUBE was used to calculate the values of the subgrade Young's modulus from the measured dynamic load-deflection curves.

b. The computer program PAVEVAL was used to determine the allowable load-carrying capacity and the required overlay thickness of the pavements at the three airport test sites.

c. The allowable load-carrying capacity and the required overlay thickness of the pavements at the three selected airport sites were calculated by the conventional destructive test methods and by the DSM method, and the results were compared with the layered elastic method.

DETERMINATION OF SUBGRADE YOUNG'S MODULUS BY VIBRATORY NONDESTRUCTIVE TESTING

MEASUREMENT OF DYNAMIC STIFFNESS MODULUS (DSM)

The WES 16-kip vibrator applies a static load of 16 kips to the pavement surface and a dynamic load up to 15 kips at frequencies ranging from 5 to 100 Hz. Both static and dynamic loads are applied to the pavement surface through a circular 18-in.-diam baseplate. Two types of vibratory nondestructive tests were performed on pavements:

a. Dynamic load-deflection curves that show the dynamic deflection of the pavement surface as a function of the applied load.

b. Frequency response spectrum curves that show the dynamic deflection as a function of frequency for a fixed dynamic load.

Only method a above is used in this study to determine the subgrade Young's modulus. In general, these dynamic load-deflection curves are nonlinear, and a nonlinear dynamic theory is required to extract the value of the subgrade Young's modulus from these measured curves. The nonlinear dynamic theory is used to remove the extraneous effects of the static and dynamic loads developed by the vibrator on the predicted values of the subgrade Young's modulus.[3,4] The computer program SUBE was developed from the nonlinear theory of pavement response to dynamic loads and is used to determine the subgrade Young's modulus from the measured dynamic load-deflection curves.

A typical dynamic load-deflection curve measured at 15 Hz is presented in Figure 1. The dynamic deflection of the pavement surface is a nonlinear function of the dynamic load applied to the pavement surface. The slope of the dynamic load-deflection curve (tangent modulus) is called the DSM. The numerical value of the DSM is obtained from the region of high dynamic loading.

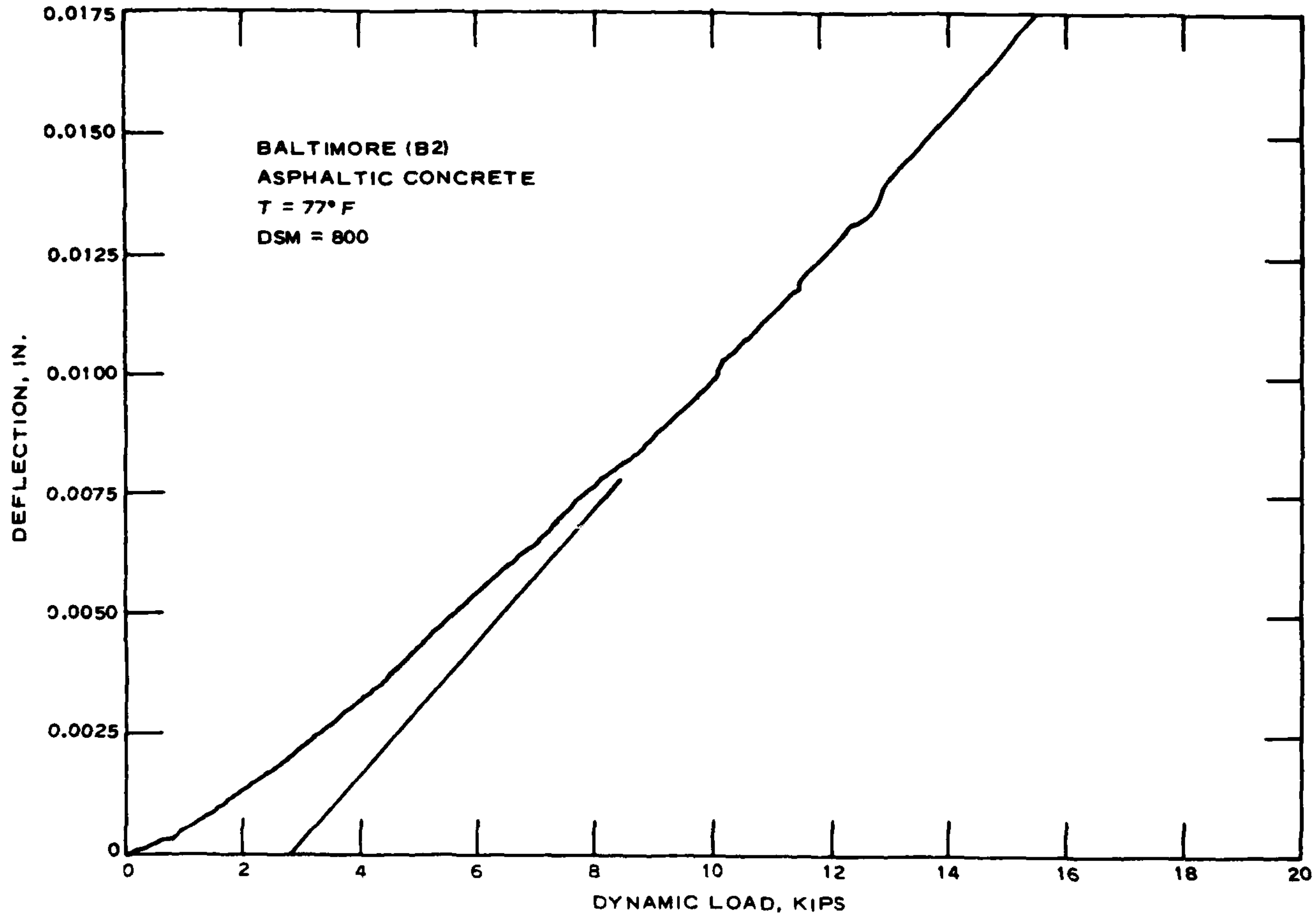


Figure 1. Typical dynamic load-deflection curve for AC pavement

DYNAMIC PAVEMENT RESPONSE
COMPUTER PROGRAM SUBE

The computer program SUBE calculates the value of the subgrade Young's modulus from input data taken from the measured dynamic load-deflection curves.[4] The pavement input parameters for the computer program SUBE include the Young's modulus, the Poisson's ratio, and the thickness of each pavement layer, as well as the Poisson's ratio of the subgrade. The computer input that is taken from vibratory nondestructive test data is the DSM value and a point-by-point description of the measured dynamic load-deflection curve. The computer program SUBE iterates the value of the subgrade Young's modulus and determines the value of the subgrade Young's modulus that makes the theoretically predicted DSM value agree with the measured DSM value so that the theoretically predicted dynamic load-deflection curve will agree with the measured dynamic load-deflection curve. Figure 2 outlines the procedure.

The Poisson's ratio of the wearing surface and base and subbase courses was chosen according to the rules $\nu = 0.2$ for PCC, $\nu = 0.3$ for AC pavements and AC base materials, and $\nu = 0.35$ for all other base and subbase materials. The Poisson's ratio for all subgrade soils is taken to be $\nu = 0.35$. A reasonable estimate of the values of the Young's modulus of base and subbase materials can be obtained from the composition of these materials.[2] When the CBR values of the base and subbase materials are known, the Young's modulus values can be estimated from the equation $E = 1500$ CBR.[9]

The Young's modulus of the PCC wearing surface of a rigid pavement is taken to be 4.0×10^6 psi. The temperature-dependent Young's modulus for AC pavement and AC base materials is obtained from Figure 3, corresponding to the pavement surface temperature at the time of the vibratory nondestructive testing. The temperature-dependent Young's modulus value is entered into the computer program SUBE to determine the subgrade Young's modulus.

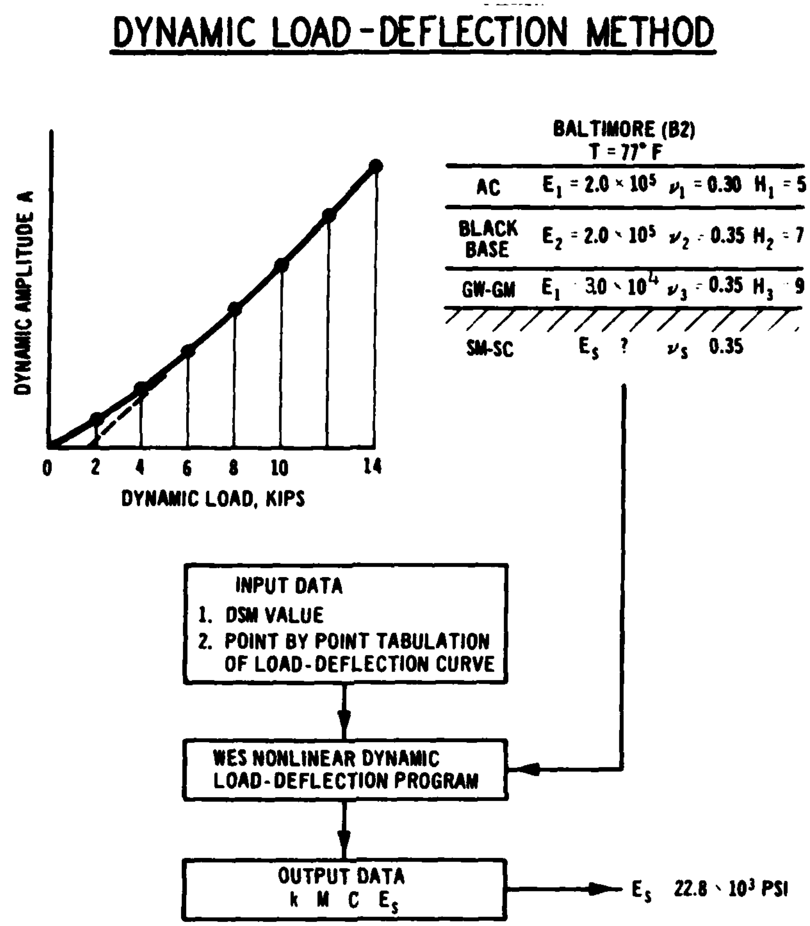


Figure 2. Outline of procedure for predicting the subgrade Young's modulus from the measured dynamic response of a pavement

LABORATORY RESILIENT MODULUS TESTS

It was planned to compare the values of the subgrade Young's modulus predicted from vibratory nondestructive field tests using the computer program SUBE with the values of the subgrade Young's modulus extracted from the laboratory resilient modulus test. The laboratory resilient modulus is expressed in terms of the applied dynamic deviator stress and the static confining pressure.[10-12]

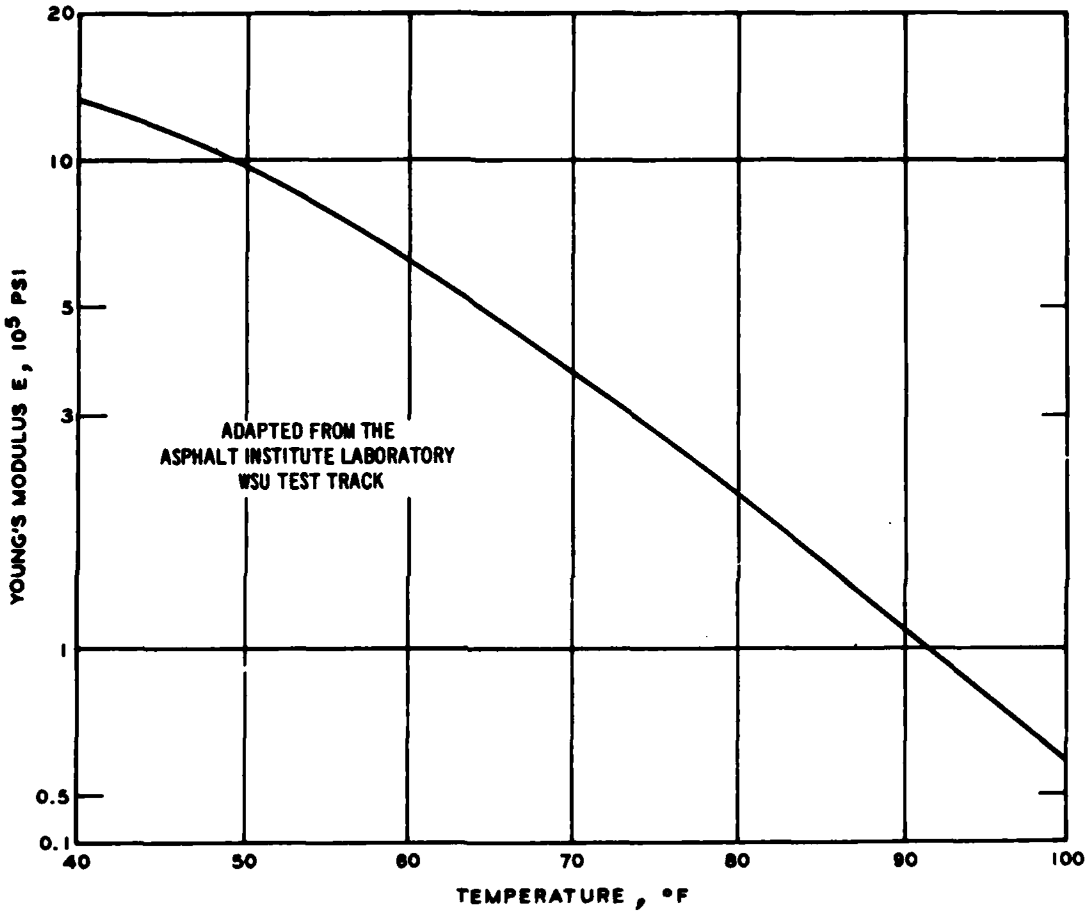


Figure 3. Assumed temperature dependence of Young's modulus of AC pavement and AC base materials

ALLOWABLE LOAD-CARRYING CAPACITY AND REQUIRED OVERLAY THICKNESS OF PAVEMENTS

COMPUTER PROGRAM PAVEVAL

Within the context of the layered elastic theory, pavements are represented by a stack of elastic layers, the subgrade being of infinite extent. This layered elastic theoretical model of a pavement structure is used to calculate the elastic stress and strain at any point in the pavement or subgrade. Each pavement layer is characterized by a Poisson's ratio (ν), a Young's modulus (E), and a layer thickness (h). The Shell BISAR computer program is based on the layered elastic theory and relates the stress and the strain in each pavement layer to the static load applied to the surface of a pavement. Figure 4 represents a typical pavement structure according to the layered elastic theory approach.

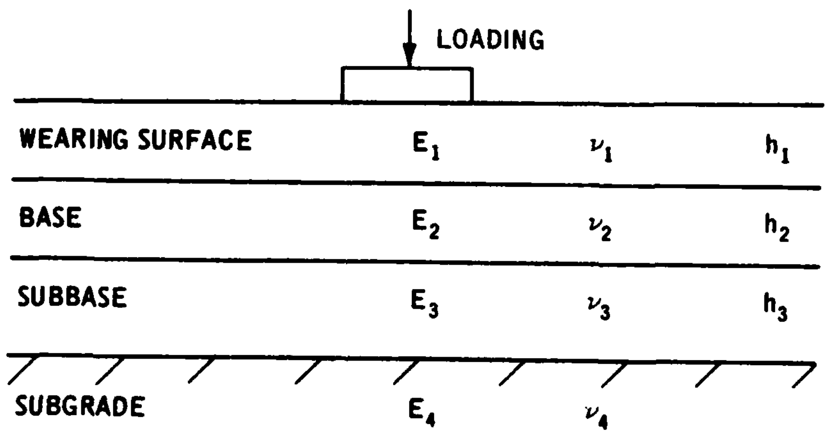


Figure 4. Typical pavement structure with loading according to layered elastic theory

Experience has shown that the condition of failure in AC pavements can be described by a limiting elastic (resilient) vertical strain in the top of the subgrade and a limiting tensile strain at the bottom of the AC pavement layer, while the condition of failure in rigid pavements can be described by a limiting tensile stress at the bottom of the PCC layer.[13,14] For a given load at the pavement surface, the values of the stress and the strain in the pavement and the subgrade depend on the Young's modulus and the Poisson's ratio of the subgrade and each pavement layer.

For the evaluation of a pavement and the determination of the required overlay thickness, the basic BISAR computer program was modified to include a procedure for iterating the surface load and the overlay thickness until the vertical strain at the top of the subgrade for AC pavements equals the limiting vertical strain value or the tensile strain at the bottom of the AC layer equals the limiting value of the tensile strain, and until the tensile stress at the bottom of the PCC layer of rigid pavements equals the limiting value of tensile stress. The resulting computer program called PAVEVAL is used to calculate the allowable load-carrying capacity and the required overlay thickness of a pavement.[7] The aircraft characteristics required for the computer program PAVEVAL include the tire contact area, the load on one wheel, wheel spacings, and the total number of main gear wheels.

The computer program PAVEVAL was written to incorporate the material parameters and the limiting stress and strain criteria into a procedure for calculating the allowable load-carrying capacity and the overlay thickness required for pavement upgrading. PAVEVAL, used in conjunction with the computer program SUBE that predicts the value of the subgrade Young's modulus, was developed to be a practical tool for the pavement engineers to use for evaluation and overlay design purposes. Figure 5 gives a flow diagram for the general procedure used for pavement evaluation and overlay design.

The choice of the elastic moduli of the pavement layers that are entered into the computer program PAVEVAL is the same as those selected for the computer program SUBE with the exception that the Young's modulus of AC pavement and AC base materials was chosen to have the value $E = 450{,}000$ psi in PAVEVAL for the numerical calculations made in this study. This value of the Young's modulus is obtained from Figure 3, corresponding to an assumed average yearly pavement temperature of 70°F. This temperature value was chosen in order to compare the results with the DSM evaluation procedure, which assumes a yearly temperature average of 70°F. However, PAVEVAL has a greater capability for pavement

1

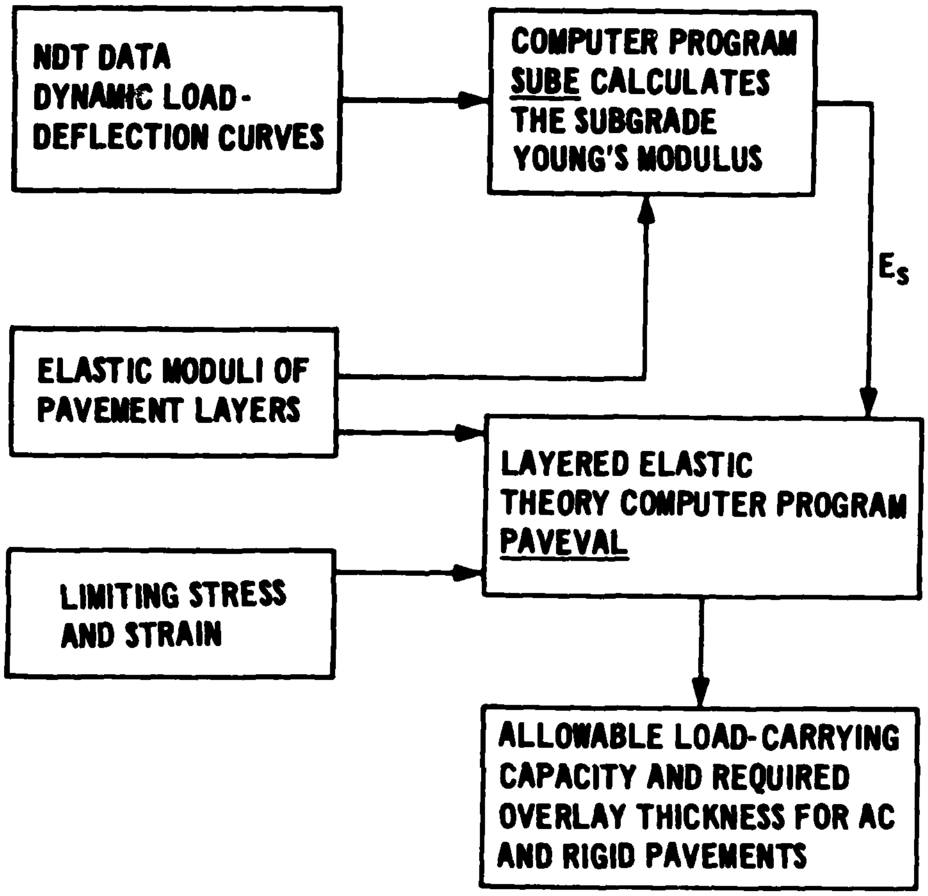


Figure 5. Pavement evaluation and overlay design by the combined methods of layered elastic theory and vibratory nondestructive testing

evaluation purposes because it can be used to study the seasonal variation of pavement allowable load-carrying capacity by using Figure 3 to select the proper seasonal variations in the value of the Young's modulus of AC pavement layers. For this purpose, the seasonal variation of the base, subbase, and subgrade Young's moduli must also be considered, such as during frost thaw conditions. The seasonal variation of these Young's moduli values may possibly be determined either by conducting vibratory nondestructive tests during the different seasons or by extrapolating laboratory-measured Young's moduli according to seasonal temperature and moisture changes.

LIMITING STRESS AND STRAIN CONDITIONS

The allowable load-carrying capacity of a pavement and the overlay thickness required for pavement upgrading are related to the limiting tensile strain at the bottom of the AC layer and to the limiting vertical strain at the top of the subgrade for AC pavements, and to the limiting tensile stress at the bottom of the PCC layer for rigid pavements.[13-15] The limiting value of the vertical strain at the top of the subgrade depends on the number of strain repetitions and on the value of the Young's modulus of the soil in the subgrade.

The lateral distribution of traffic was handled by using pass-to-coverage ratios for individual aircraft.[16,17] Mixed traffic was not considered in this study, but it can be incorporated into PAVEVAL provided the frequency distribution of operating aircraft is known.

SINGLE- AND MULTIPLE-WHEEL LOADINGS

To determine the allowable load-carrying capacity and the required overlay thickness for a single-wheel loading on a pavement surface, the stress and the strain due to the single load are compared with the limiting stress and strain values in the pavement and the subgrade. The load on one wheel is entered into the computer program PAVEVAL.

Actual aircraft loadings on a pavement occur through two or more wheels in close proximity. Dual-wheel (two-wheel) and dual-tandem-wheel (four-wheel) configurations are commonly used. For the case of multiple wheels, the total strain or stress in the pavement beneath one wheel is due in part to the presence of the other wheels. The maximum values of the stress and the strain at some depth in the pavement occur at a point between the wheels. However, a good approximation of these maximum values can be obtained by calculating the values of the stress and the strain at the same depth in the pavement and directly beneath one of the wheels. The multiple-wheel calculations in the computer program PAVEVAL are made within this approximation. PAVEVAL, as well as the BISAR program on which it is based, calculates the stress and the strain at any point in the pavement due to a multiple-wheel loading and can also compare them to their corresponding limiting values.

VALIDATION

LABORATORY AND FIELD SOIL TESTS

Laboratory soil classification tests were performed on the samples taken from the base, subbase, and subgrade at the three airport pavement sites investigated. Field measurements of the thickness and the CBR were also made of the base, subbase, and subgrade materials by drilling core holes (small aperture tests[18]). The coefficient of subgrade reaction that is required for the Westergaard calculation of PCC pavement strength using the Westergaard theory was obtained indirectly from measurements of the subgrade CBR.[18] The Young's moduli of the material in the pavement layers was calculated from the formula $E = 1500$ CBR.[9] The mean pavement temperature was measured for AC wearing surfaces at the time the vibratory nondestructive tests were conducted. Tables 1-3 present the results of the field and laboratory tests.

The subgrade soils at the three airport sites were inhomogeneous, and accurate CBR measurements could not be made. The subgrade soil at the Knox County Airport, Rockland, Maine, contained rocks and boulders, and at the Minneapolis-St. Paul International Airport, the subgrade often was a thin layer of soil overlying bedrock.

Laboratory resilient modulus values were also measured for a series of dynamic deviator stresses and static confining pressures on undisturbed subgrade soil samples taken from the pavement sites. Most of the subgrade soil samples taken from the Rockland and Minneapolis-St. Paul sites were too poor in quality to perform resilient modulus tests, but the subgrade soil samples from the Albuquerque site produced some resilient modulus measurements. Figures 6-15 show the results of the resilient modulus measurements.

NUMERICAL VALUES OF THE PREDICTED SUBGRADE YOUNG'S MODULUS

At each pavement location, four dynamic load-deflection curves were measured at 15 Hz. The computer program SUBE was used to determine a predicted value of the subgrade Young's modulus for each measured

Table 1. Pavement Structures Investigated at Albuquerque Sunport

Location			Wearing Surface						Base Course					Subbase Course					Subgrade					
Drill Site No.	Feature	Sta	Material	T °F	R psi	E_1 10^6 psi	ν_1	h_1 in.	Material*	CBR	E_2 10^3 psi	ν_2	h_2 in.	Material*	CBR	E_3 10^3 psi	ν_3	h_3 in.	Material	CBR	E_4 (1500 CBR) 10^3 psi	E_4 (SUMS) 10^3 psi	ν_4	DSM kips/in.
1	R/W 17-35	6+13	PCC	--	600	4.0	0.2	12	--	--	--	--	--	--	--	--	--	--	SM silty sand	20	30	22.3	0.35	2013
2	R/W 17-35	19+00	AC	62.4	--	0.5	0.3	3	Cement stab. base	100+	150	0.35	9	--	--	--	--	--	SM gravelly, silty sand	54	81	46.5	0.35	850
3	R/W 17-35	100+07	PCC	--	700	4.0	0.2	6	--	--	--	--	--	--	--	--	--	--	SC clayey sand	13	19.5	--	0.35	632
4	North warm-up apron	--	PCC	--	700	4.0	0.2	9	--	--	--	--	--	--	--	--	--	--	SC clayey sand	25	37.5	--	0.35	1457
5	T-1	7+00	AC	75.2	--	0.3	0.3	7	SC	83	125	0.35	6	SM	75	113	0.35	5	SC silty sand	20	30	27.5	0.35	971
6	T-1	21+00	AC	68.1	--	0.4	0.3	5	SM	100+	150	0.35	12	--	--	--	--	--	SC-SM silty sand	25	37.5	27.8	0.35	832
7	T-3D	2+00	AC	82.7	--	0.2	0.3	2	SC-SM	91	137	0.35	12	--	--	--	--	--	SC-SM silty sand	38	57	16.0	0.35	601
8	R/W 3-21	9+00	AC	54.3	--	0.8	0.3	4.5	SM	34	51	0.35	9	--	--	--	--	--	SM-SC clayey silty sand	18	27	12.8	0.35	563
9	R/W 12-30	1+05	PCC	--	780	4.0	0.2	6	SC-SM	36	54	0.35	10	--	--	--	--	--	ML silty sand	14	21	7.0	0.35	930
10	R/W 12-30	30+00	AC	85.8	--	0.16	0.3	6	SC-SM	91	137	0.35	11**	--	--	--	--	--	SM silty sand	54	81	26.6	0.35	912
11	T-2	9+00	AC	82.1	--	0.2	0.3	6	SC-SM	98	147	0.35	6	--	--	--	--	--	ML silty sand	26	39	19.1	0.35	729
12	T-2	56+00	AC	82.2	--	0.2	0.3	4	SC	54	81	0.35	8**	--	--	--	--	--	SC clayey sand	15	22.5	12.4	0.35	654
13	T-2	48+00	AC	83.1	--	0.2	0.3	5.5	SC	54	81	0.35	10**	--	--	--	--	--	SC silty sand	16	24	19.0	0.35	706
14	T-6	4+12.5	PCC	--	500	4.0	0.2	20	--	--	--	--	--	--	--	--	--	--	SM silty sand	35	52.5	20.8	0.35	4175
15	T-3B	2+00	AC	85.4	--	0.16	0.3	3	SC-SM	95	143	0.35	10	--	--	--	--	--	SC-SM silty sand	55	82.5	22.2	0.35	594
16	T-8	21+00	AC	92.0	--	0.09	0.3	8	SC-SM	91	137	0.35	7	--	--	--	--	--	SC-SM silty sand	41	61.5	--	0.35	752
17	T-8	37+00	AC	54.6	--	0.8	0.3	4.5	SC-SM	100+	150	0.35	9	SM	57	86	0.35	5	SC-SM silty sand	48	72	45	0.35	1018

* All base course material is gravelly, silty sand and caliche.
** There is 1 in. of asphalt-treated base above the base course.

Table 2. Pavement Structures Investigated at Knox County Airport, Rockland Maine

Location			Wearing Surface					Base Course					Subgrade					
Drill Site No.	Feature	Sta	Material	Temp. °F	E_1 10^3 psi	ν_1	h_1 in.	Material	CBR	E_2 10^3 psi	ν_2	h_2 in.	Material	CBR	E_4 (1500 CBR) 10^3 psi	E_4 (SUBE) 10^3 psi	ν_4	DSM kips/in.
1	R/W 21	3+00	AC	75	280	0.3	3.5	Crushed stone P-209	33	49.5	0.35	20	CL sandy clay with gravel	13	19.5	7.9	0.35	527
2	R/W 21	23+00	AC	77	260	0.3	3.25	Crushed stone P-209	35	52.5	0.35	5.75		19	28.5	19.8	0.35	552
3	R/W 21	37+00	AC	81	220	0.3	3	Crushed Stone P-209	52	78	0.35	6	CL sandy clay	2.5	3.75	18.6	0.35	620
4	T-B	22+00	AC	78	240	0.3	3.25	Crushed Stone P-209	40	60	0.35	7.25	CL sandy clay	2.5	3.75	9.0	0.35	470
5	Ramp	15+00A	AC	72	320	0.3	3.25	Crushed stone P-209	43	64.5	0.35	4.75	SM silty sand with gravel	2.5	3.75	4.5	0.35	397
6	R/W 13	42+00	AC	74	290	0.3	4.375	Crushed stone P-208	19	28.5	0.35	24+		14	21.0	--	0.35	--
7	R/W 13	30+00	AC	76	270	0.3	4	Crushed stone P-208	37	55.5	0.35	18	CL lean clay with sand	14	21.0	8.0	0.35	478
8	R/W 13	2+65	AC	79	230	0.3	3	Crushed stone P-208	10	15	0.35	24+		14	21.0	14.0	0.35	567
9	T-A	6+00	AC	75	280	0.3	3.5	Crushed stone P-209	39	58.5	0.35	27+		2.5	3.75	--	0.35	--

Table 3. Pavement Structures Investigated at Minneapolis-St. Paul International Airport

Location			Wearing Surface					Base Course					Subbase Course					Subgrade					
Drill Site No.	Feature	Sta	Material	Temp.* Flex. Str.**	E_1 10^6 psi	ν_1	h_1 in.	Material	CBR	E_2 10^3 psi	ν_2	h_2 in.	Material	CBR	E_3 10^3 psi	ν_3	h_3	Material	CBR	E_4 (1500 CBR) 10^3 psi	E_4 (CUBE) 10^3 psi	ν_4	DBM kips/in.
1	R/W 11L-29R	5+65	PCC	740	4.0	0.2	12.75	Crushed stone	81	121.5	0.35	7.75	--	--	--	--	--	SM silty sand	61	91.5	27.3	0.35	3150
2		49+95	PCC	608	4.0	0.2	11.0	Crushed stone	49	73.5	0.35	7.5	--	--	--	--	--	SM silty sand	30	45	35.8	0.35	2648
3	R/W 11R-29L	7+15	AC/PCC	64.2° 896	0.5 4.0	0.3 0.2	8.5 AC 9.5 PCC	--	--	--	--	--	--	--	--	--	--	SM silty sand	24	36	203.0	0.35	3480
4		78+30	AC/PCC	63.75 822	0.51 4.0	0.3 0.2	8.0 AC 14.0 PCC	Crushed stone	54	81.0	0.35	5.75	--	--	--	--	--	SM silty sand	64	96	216.0	0.35	5830
5	R/W 4R-22L	4+35	PCC	783	4.0	0.2	11.0	Crushed stone	78	117	0.35	9.25	--	--	--	--	--	SP-SM sand	11	16.5	31.8	0.35	1835
6		62+47	PCC	675	4.0	0.2	14.5	Crushed stone with fines	83	124.5	0.35	7.5	--	--	--	--	--	SC clayey sand with gravel	75	112.5	233.0	0.35	4740
7	T/W 11L-29R	3+00	PCC	858	4.0	0.2	12.0	Sandy gravel	100+	150	0.35	6.0	--	--	--	--	--	SM silty sand	31	46.5	223.0	0.35	3880
8	T/W 11R-29L	4+75	PCC	723	4.0	0.2	13.25	Crushed stone with fines	41	61.5	0.35	12.75	--	--	--	--	--	SP-SM sand	100+	150	183.0	0.35	6700
9	T/W 4R-22L	1+72	PCC	865	4.0	0.2	11.0	--	--	--	--	--	--	--	--	--	--	SP-SM sand with gravel	27	40.5	18.0	0.35	1840
10	New reserve taxiway	7+34	PCC	774	4.0	0.2	16.9	Crushed lime-stone	70.5	105.8	0.35	6.38	--	--	--	--	--	SM gravelly, silty sand	--	--	35.3	0.35	2955
11	East side taxiway	12+45	PCC	773	4.0	0.2	15.63	Crushed stone	72.5	108.8	0.35	8.0	--	55.5	83.3	0.25	72	SM silty sand	--	--	--	0.35	7760
12	Old north ramp		PCC	736	4.0	0.2	11.0	--	--	--	--	--	--	--	--	--	--	SC clayey sand	13.0	19.5	70	0.35	1720
13	Old ramp		AC/PCC	61.9° 902	0.57 4.0	0.3 0.2	2.25 AC 5.25 PCC	--	--	--	--	--	--	--	--	--	--	SM silty sand	8.0	12	11	0.35	910
14	Ramp		PCC	723	4.0	0.2	14.5	Silty sandy gravel	14	21	0.35	8.5	--	--	--	--	--	SC ML-CL	10.5	15.8	15	0.35	5420

* Temperature on AC/PCC pavements, °F
** Flexural strength of concrete, psi

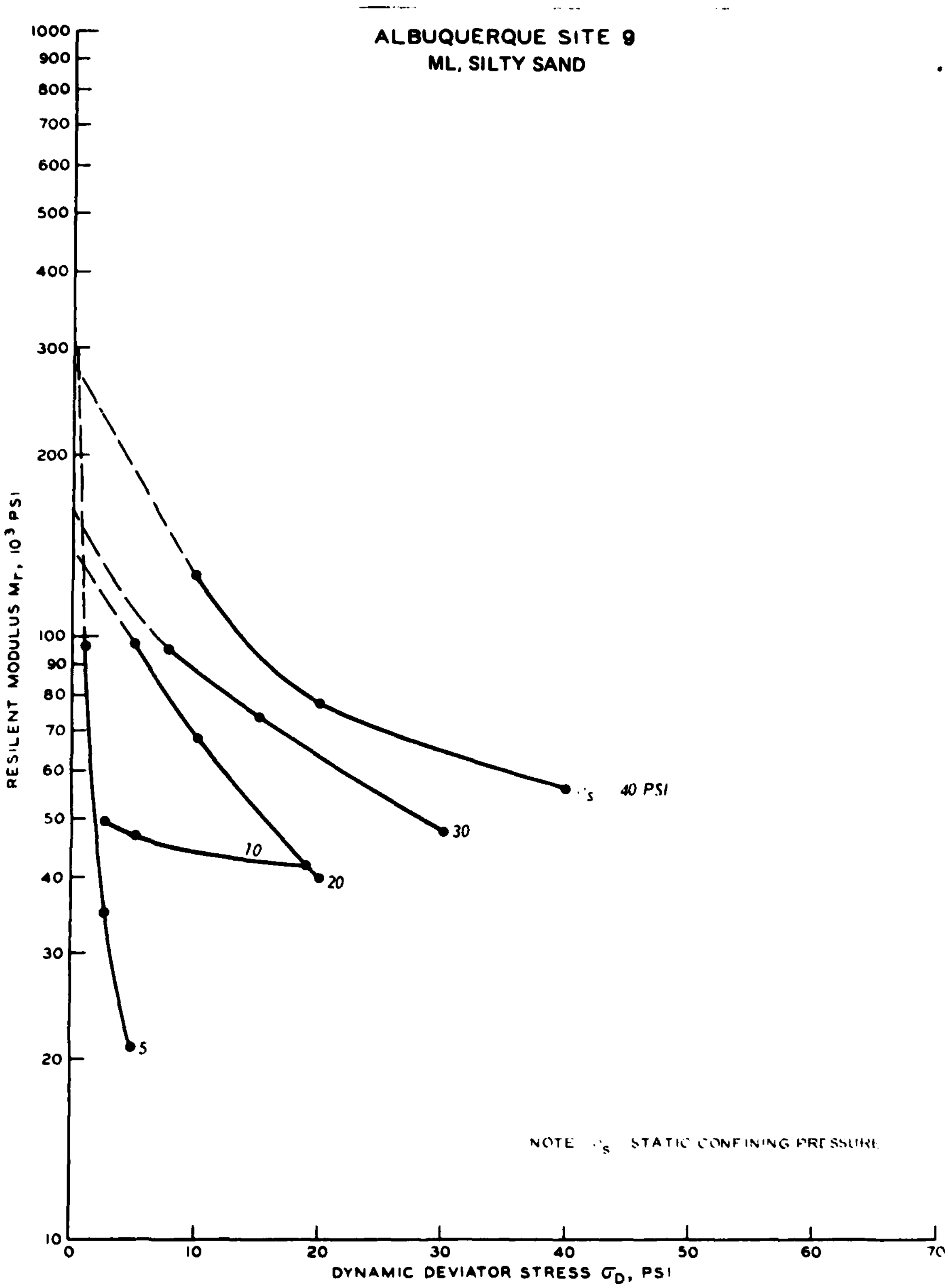


Figure 6. Resilient modulus test, Albuquerque-9

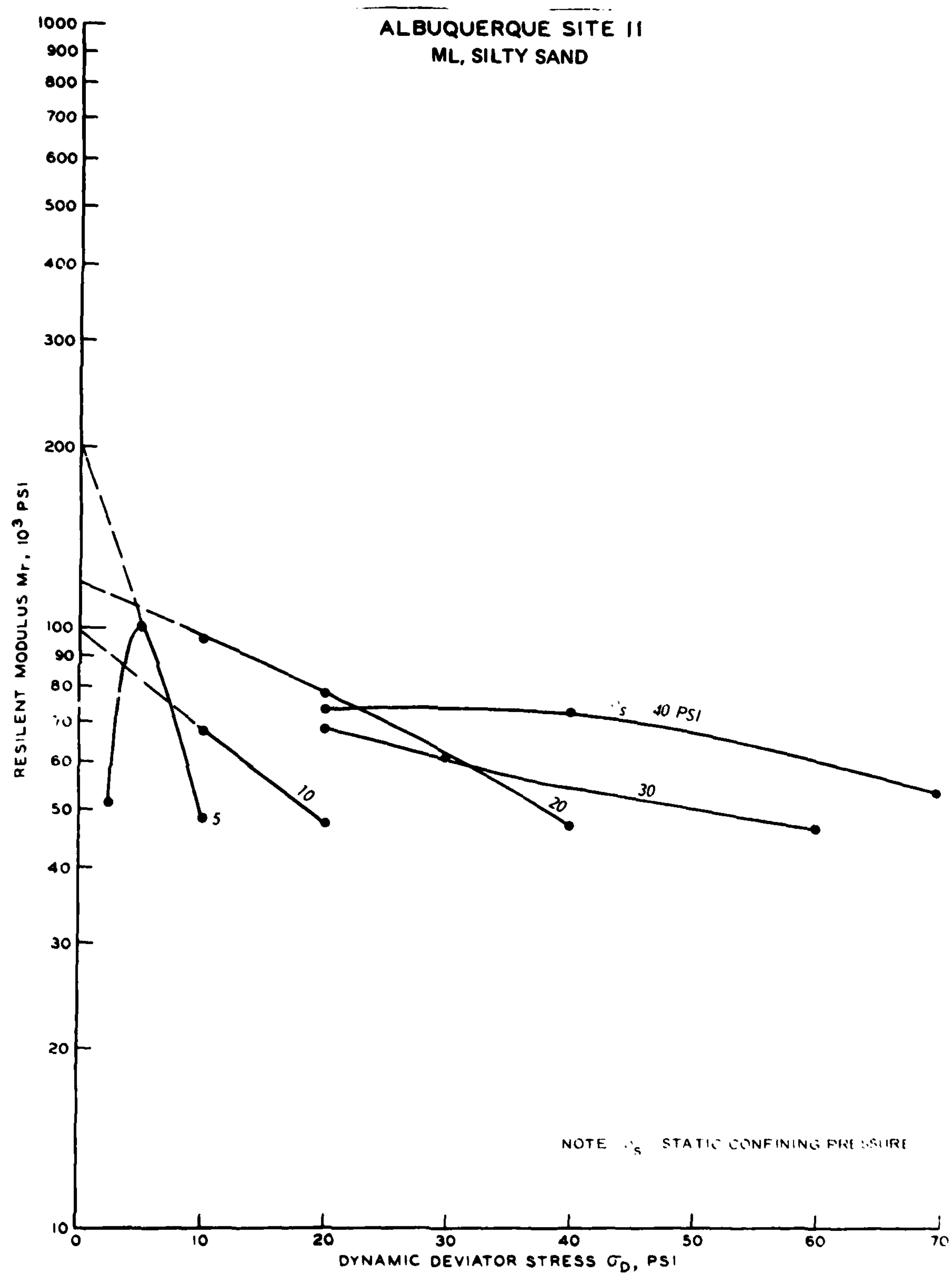


Figure 7. Resilient modulus test, Albuquerque-11

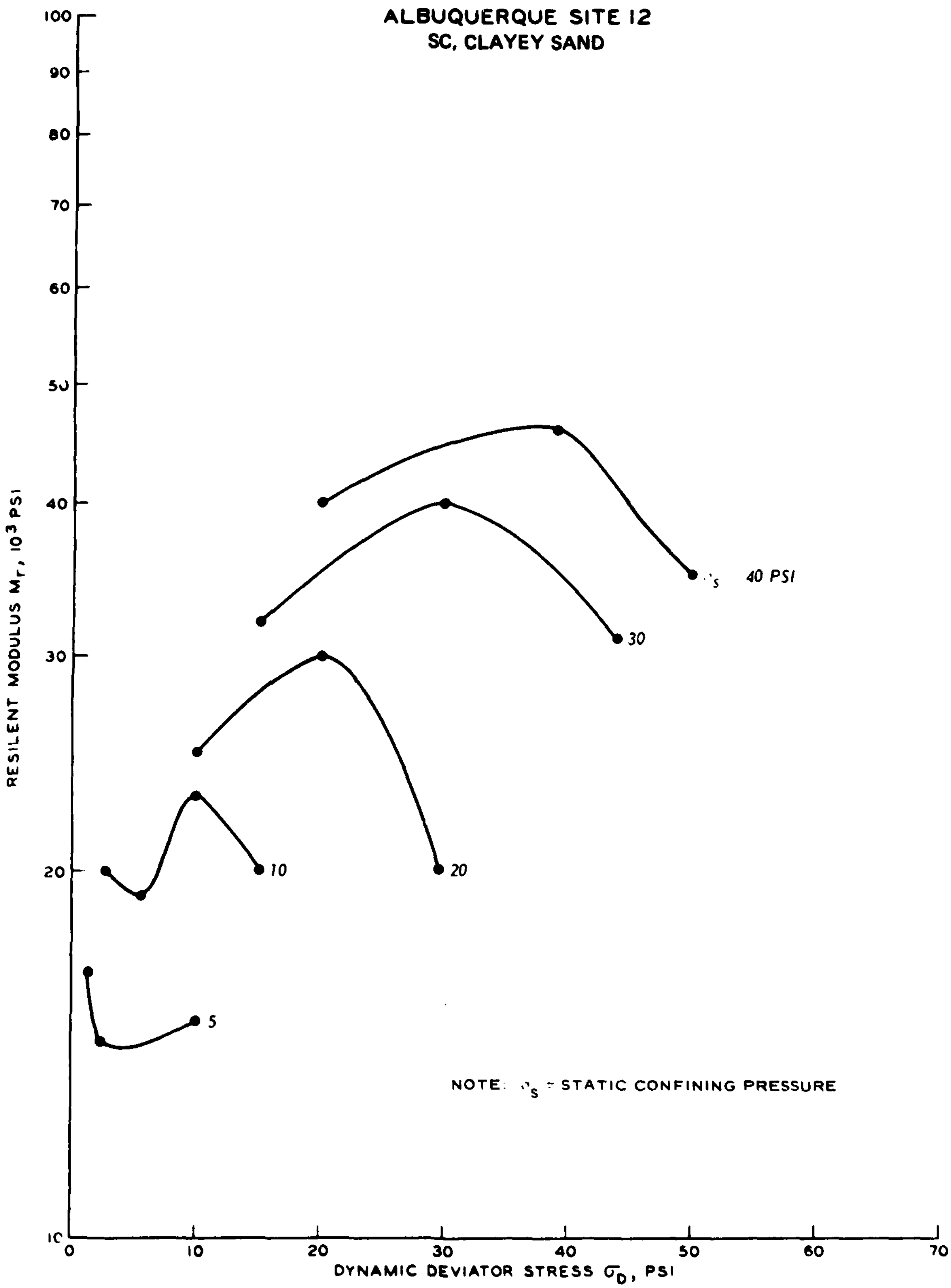


Figure 8. Resilient modulus test, Albuquerque-12

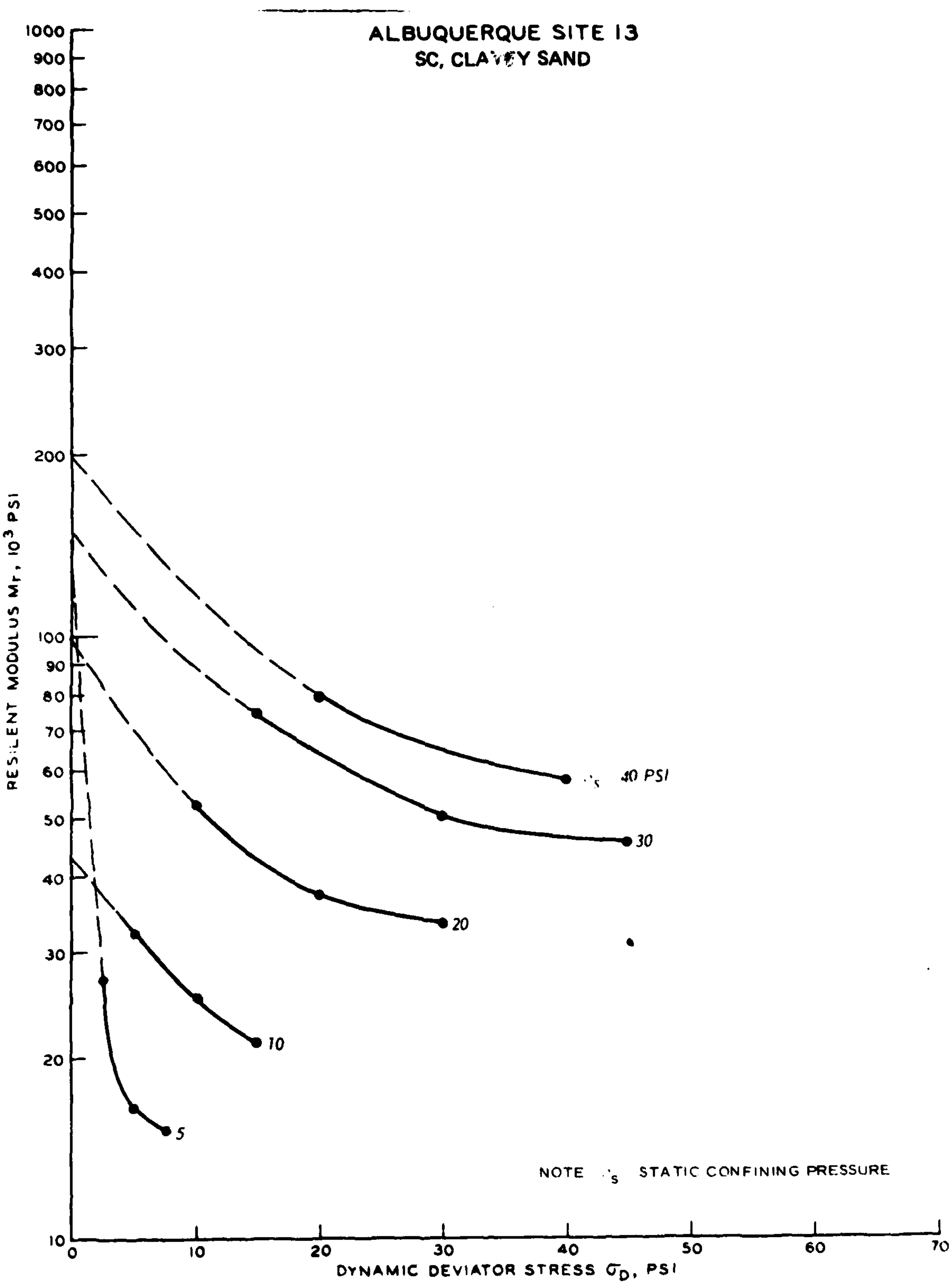


Figure 9. Resilient modulus test, Albuquerque-13

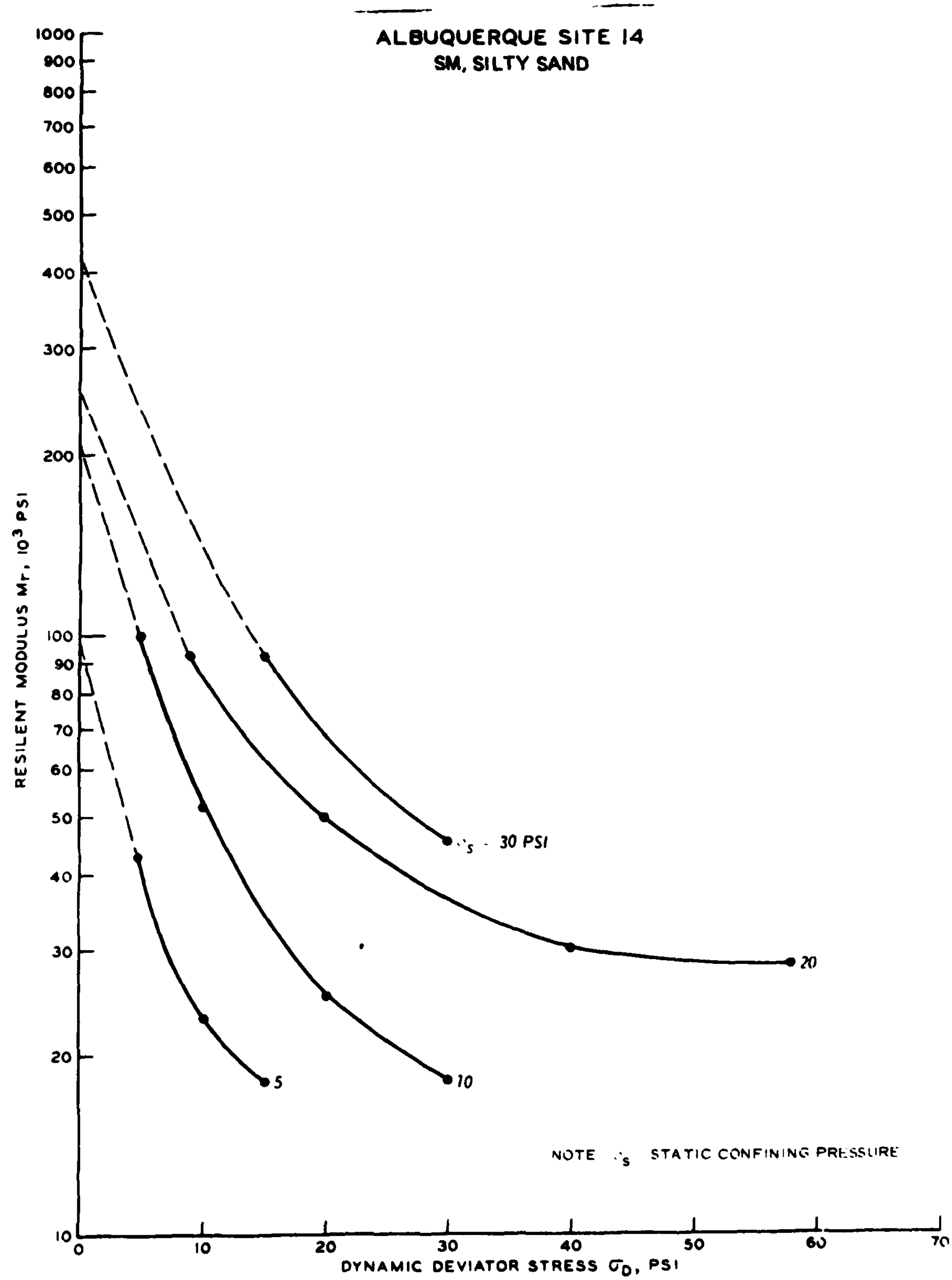


Figure 10. Resilient modulus test, Albuquerque-14

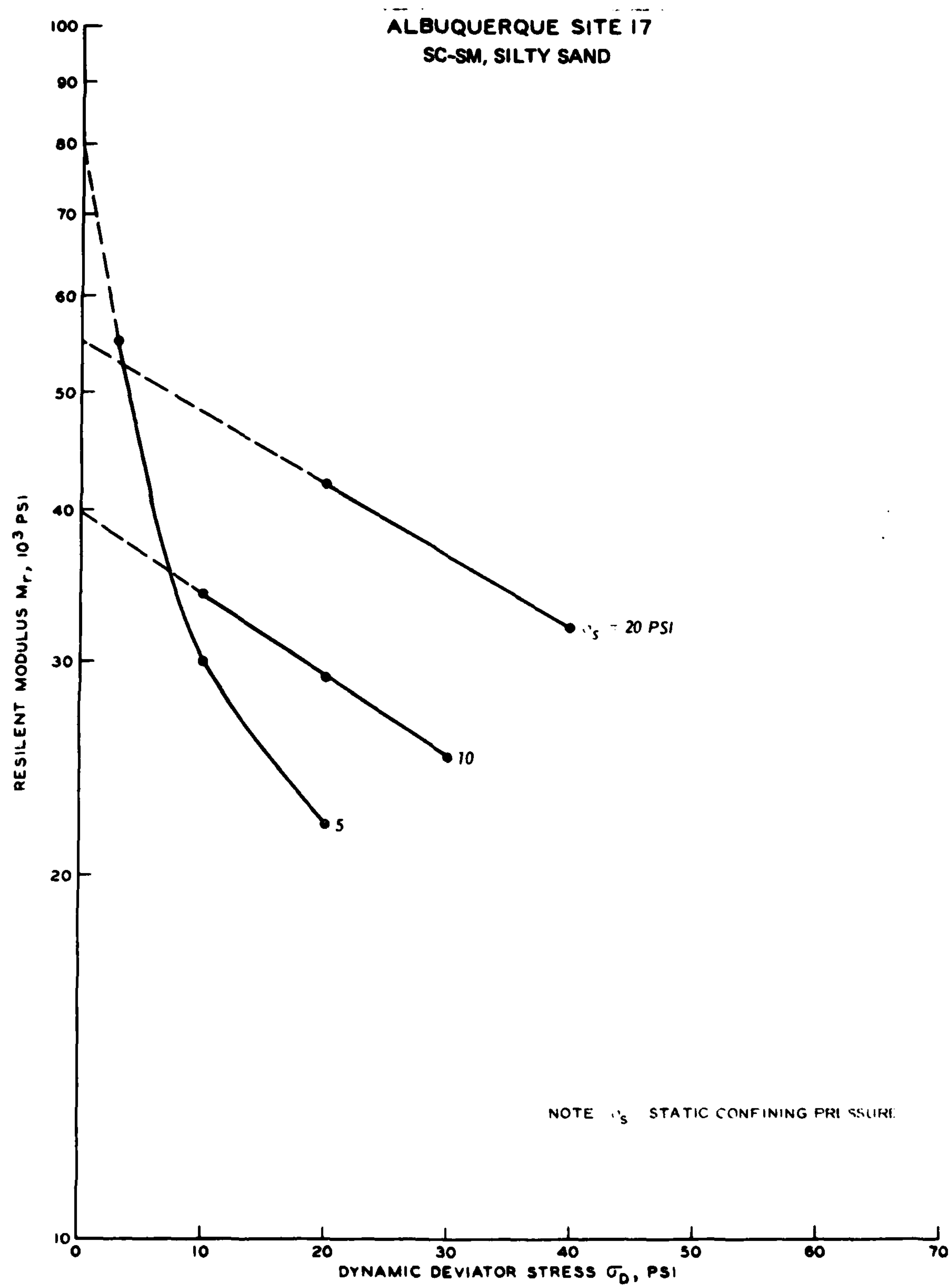


Figure 11. Resilient modulus test, Albuquerque-17

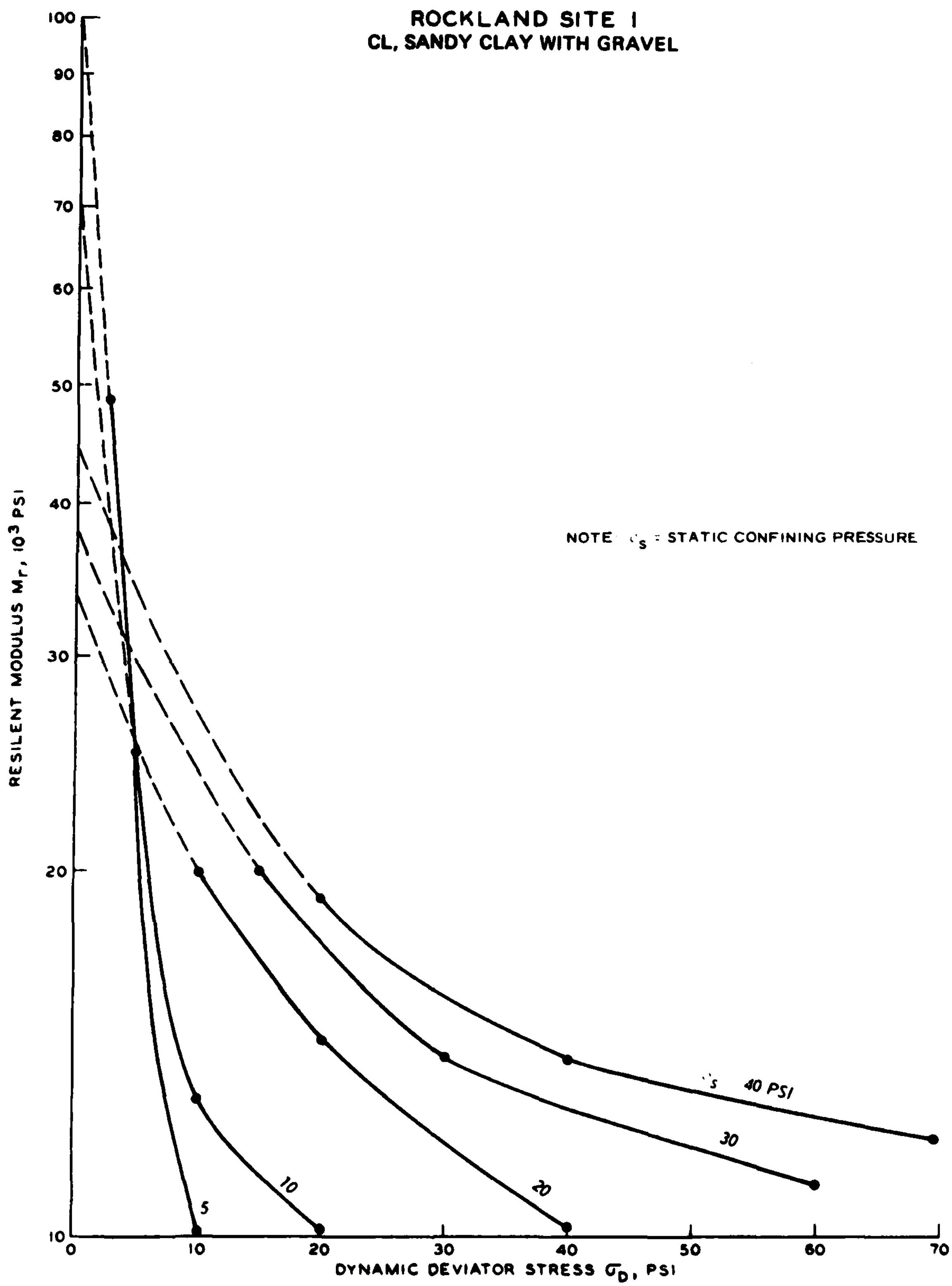


Figure 12. Resilient modulus test, Rockland-1

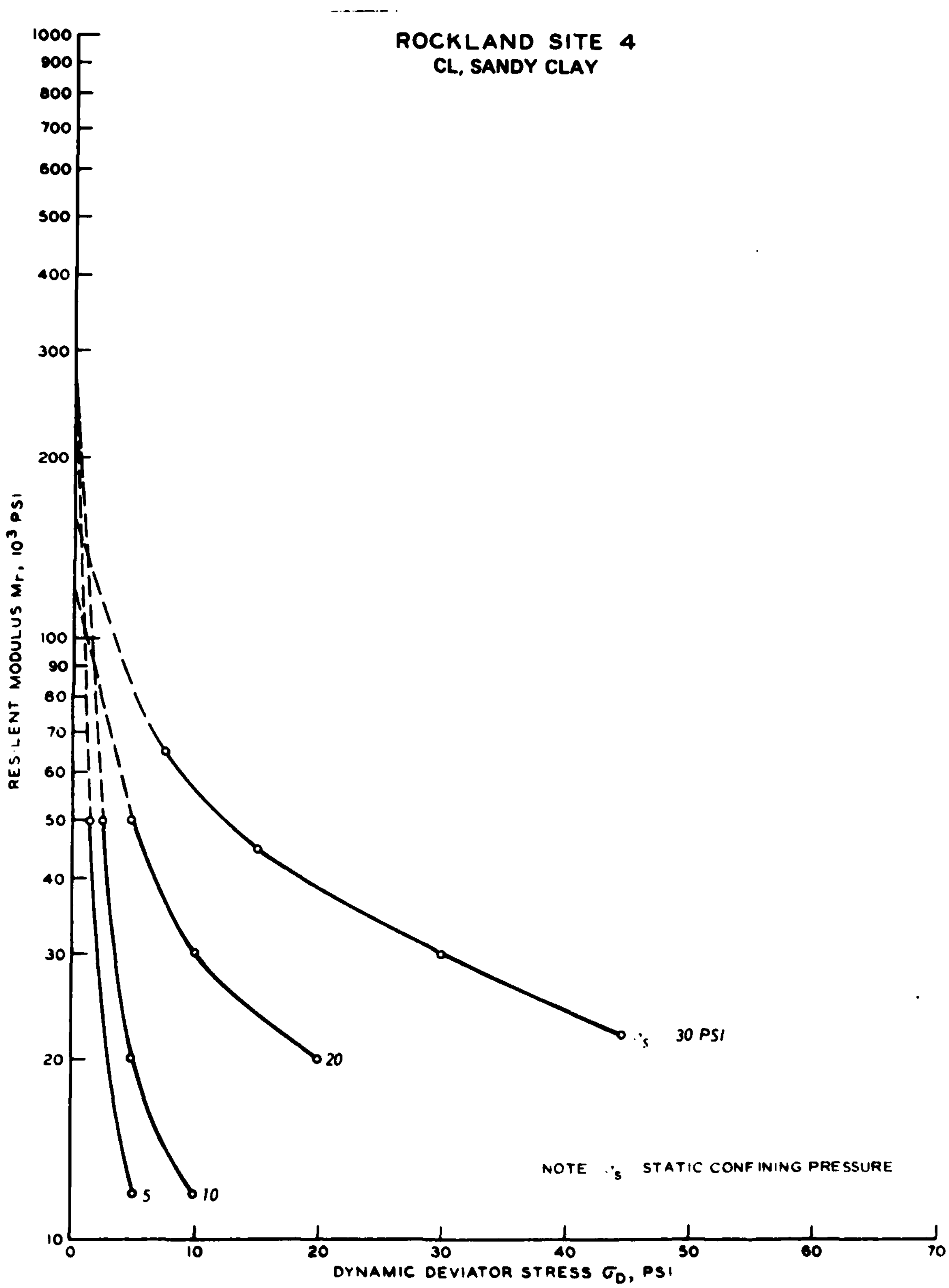


Figure 13. Resilient modulus test, Rockland-4

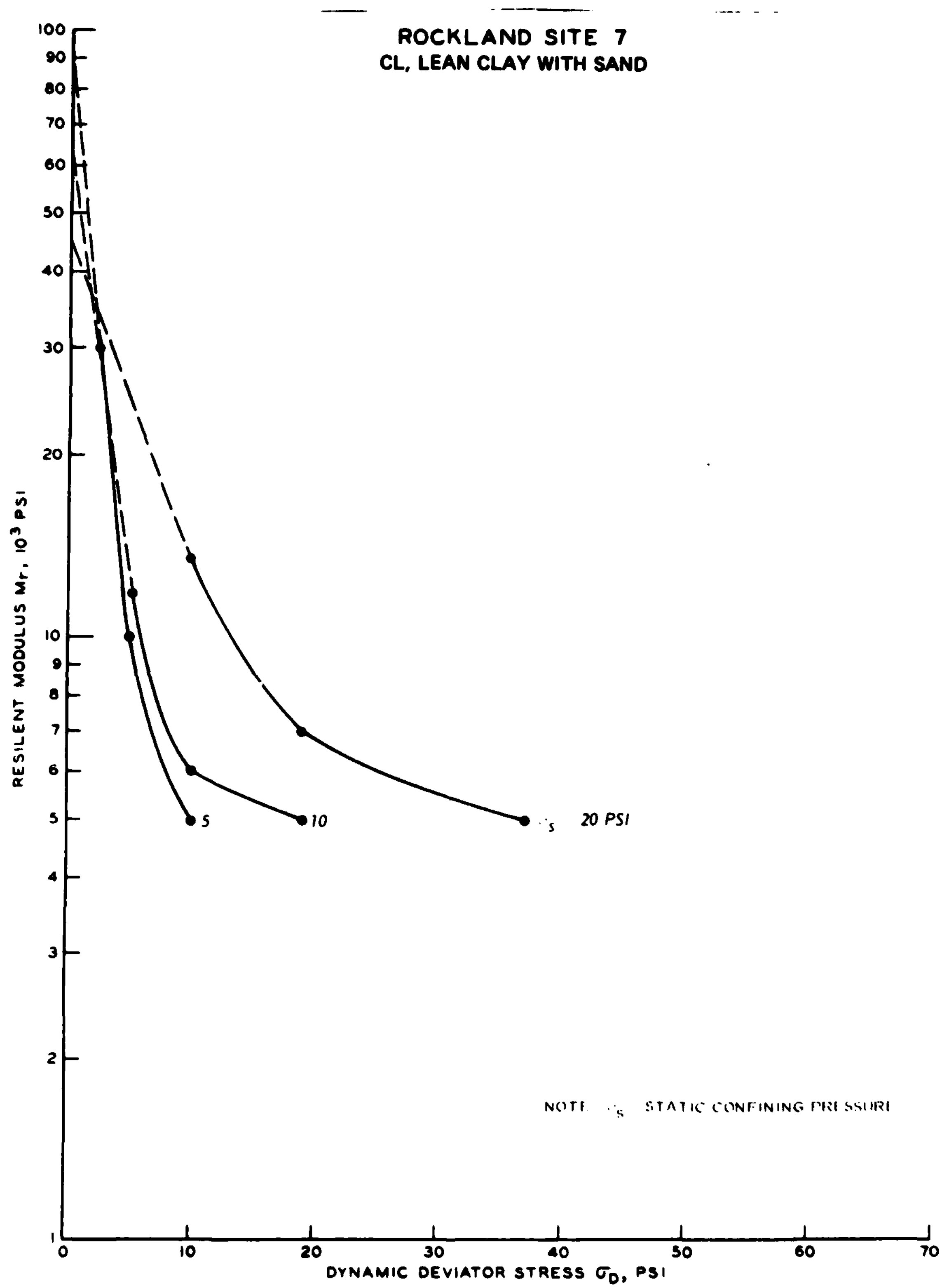


Figure 14. Resilient modulus test, Rockland-7

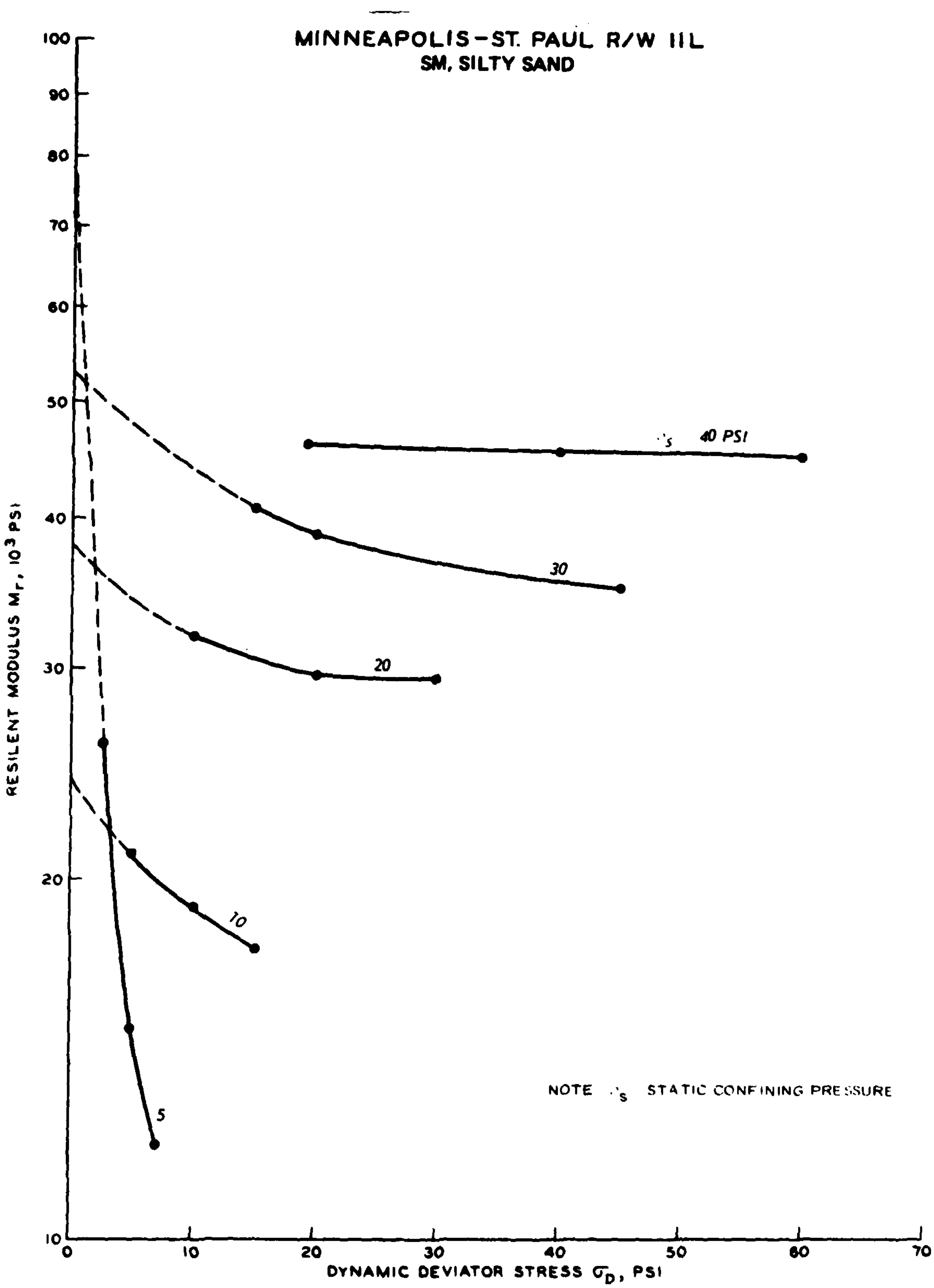


Figure 15. Resilient modulus test, Minneapolis-St. Paul-11L

dynamic load-deflection curve. The set of predicted Young's moduli at each location was averaged, and this average value of the subgrade Young's modulus appears in Tables 1-3 for each test location at the three airport sites. The four values of the Young's modulus predicted at each location did not vary by more than 15 percent, so the average value represents the subgrade Young's modulus for a given location.

A simple relationship between the subgrade Young's modulus and the CBR has been obtained by wave propagation techniques and is given by the empirical formula $E_s = 1500$ CBR, where E_s represents the subgrade Young's modulus. The nonlinear dynamic theory of pavement response and the associated computer program SUBE were developed to predict values of the subgrade Young's modulus that are in reasonable agreement with the predictions of $E_s = 1500$ CBR.

Figure 16 shows a comparison of the subgrade Young's modulus values predicted by the nonlinear dynamic response theory through the computer program SUBE and the subgrade Young's modulus values derived from the empirical formula $E_s = 1500$ CBR. Figures 17 and 18 give a comparison between the values of the subgrade Young's modulus obtained from the laboratory resilient modulus tests and from the SUBE and 1500 CBR methods, respectively.

The Young's modulus of a soil can be extracted from the resilient modulus that is measured in the laboratory.[4] The resilient modulus is a measure of the response of a soil to dynamic loads. Its value depends on both the static and dynamic loads. The Young's modulus is a measure of the response of a soil to static loads, and its value depends only on the static confining pressure. The resilient modulus and the Young's modulus cannot be used interchangeably. The extraction of the Young's modulus from the resilient modulus by the method given in Reference 4 was not done for this validation report. Instead, as a first approximation, the values of the resilient modulus for zero dynamic load were used to obtain the Young's modulus values for the comparison with 1500 CBR shown in Figures 17 and 18.

The choice of zero dynamic load is made because the Young's modulus is a static elastic quantity that is defined for zero dynamic

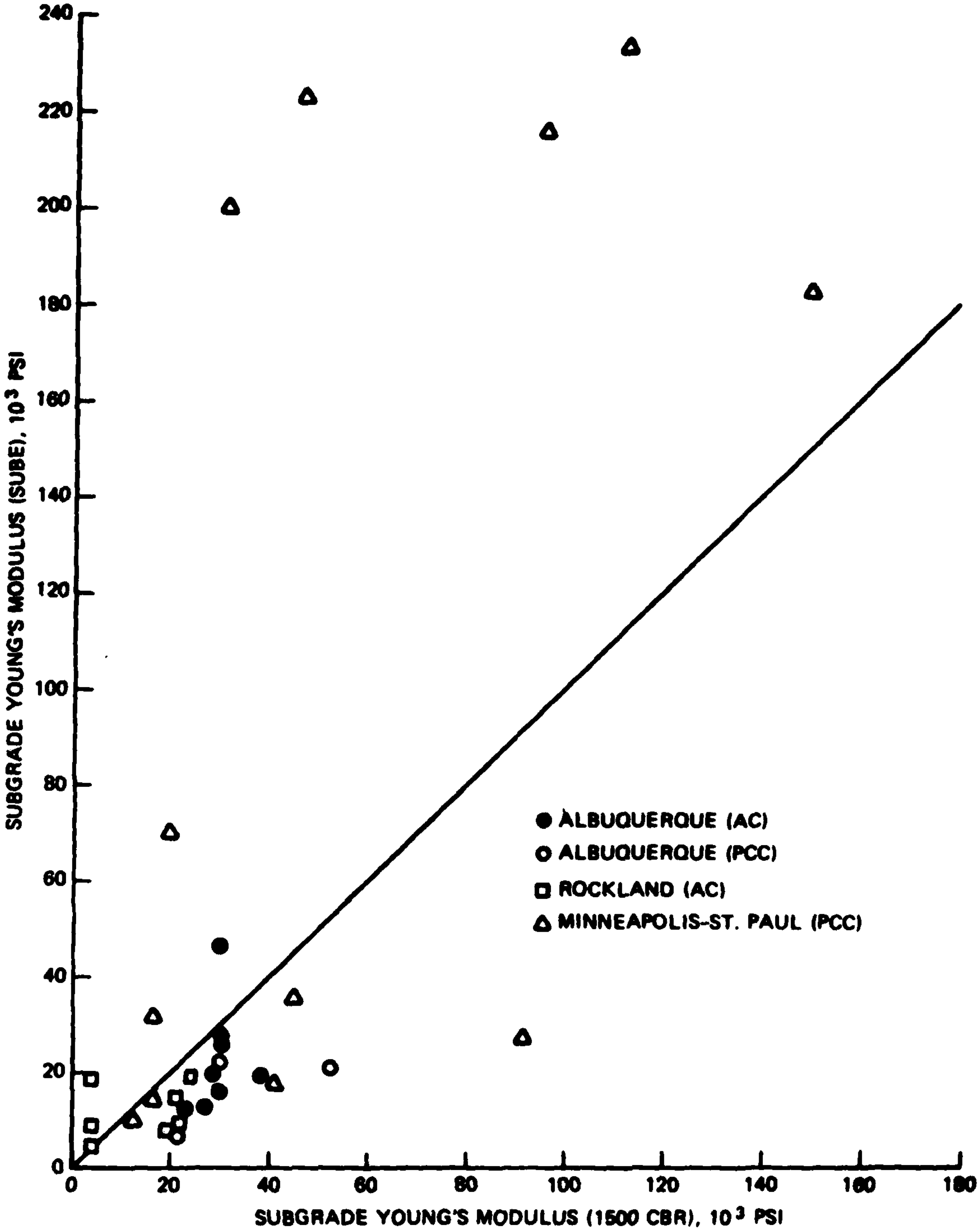


Figure 16. Comparison of predicted and measured subgrade Young's moduli

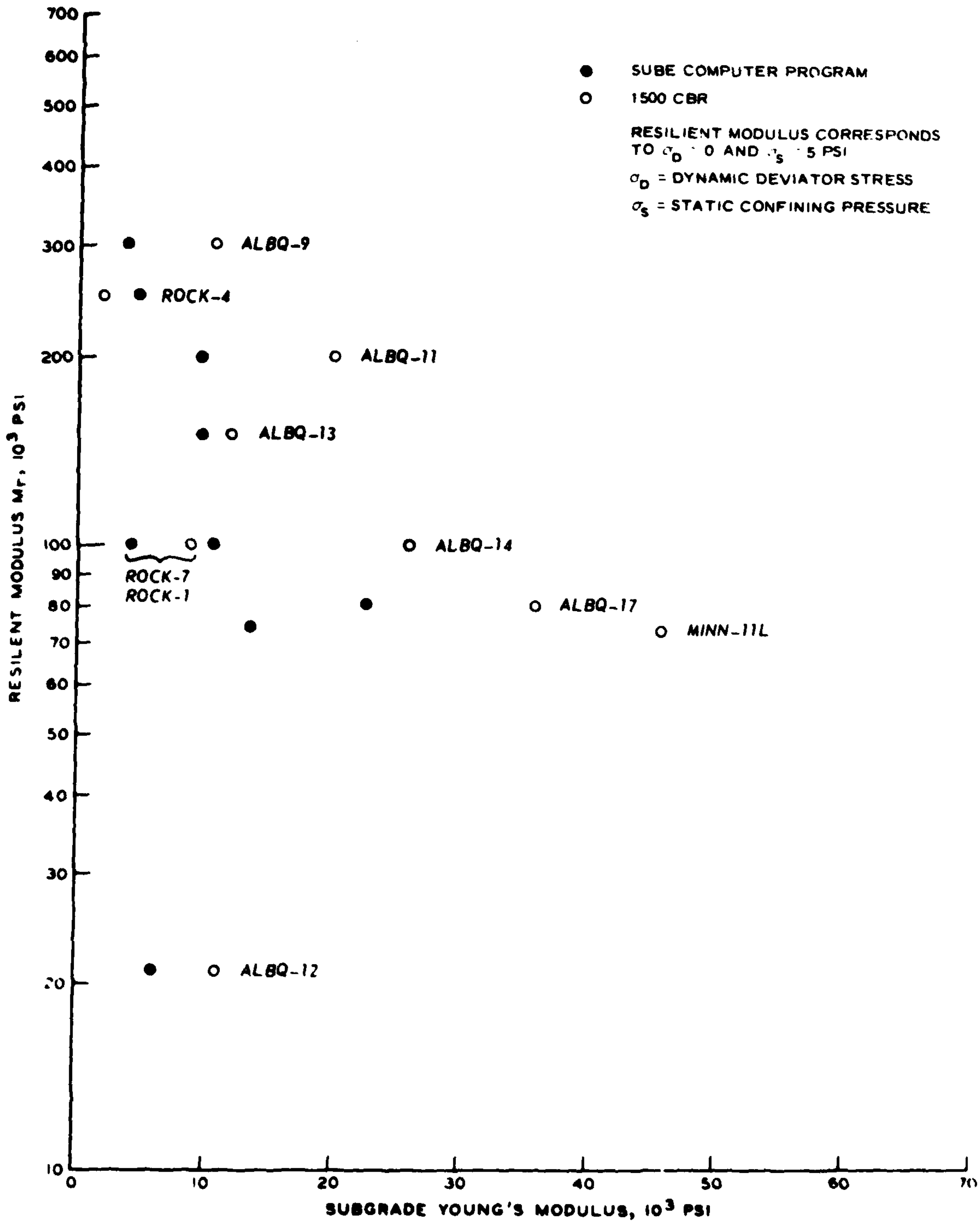


Figure 17. Comparison of values of the subgrade Young's modulus as predicted by SUBE, by 1500 CBR, and by extraction from the laboratory resilient modulus test at $\sigma_s = 5$ psi

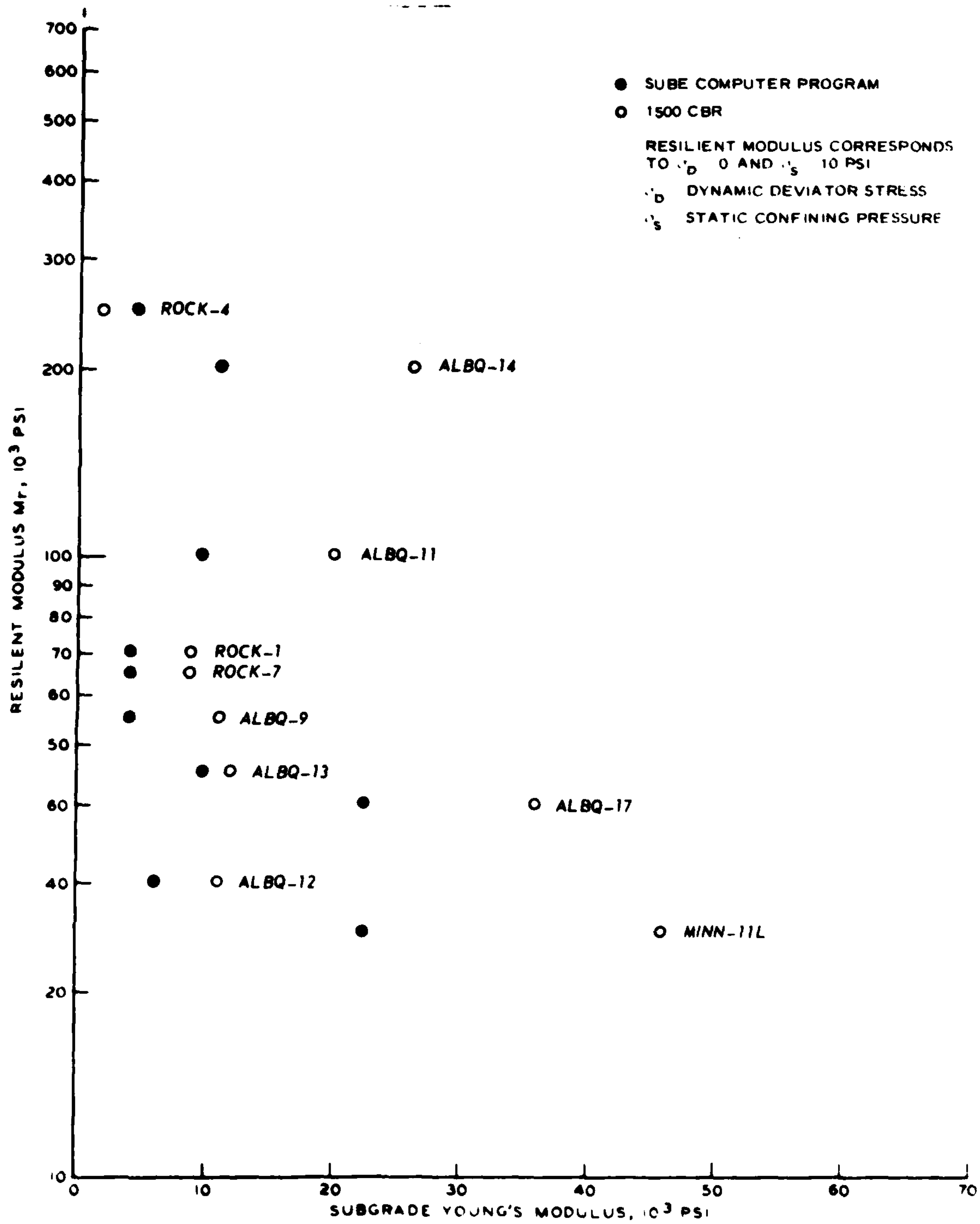


Figure 18. Comparison of values of the subgrade Young's modulus as predicted by SUBE, by 1500 CBR, and by extraction from the laboratory resilient modulus test at σ_s = 10 psi

loads. Furthermore, the CBR measurement is made under static loading conditions, and it should likewise be compared with a static elastic modulus--the Young's modulus extracted from the resilient modulus. Finally, the formula $E = 1500$ CBR is determined from wave propagation tests under vanishingly small dynamic pressures, so that the Young's modulus determined in this way refers essentially to zero dynamic loading. No doubt better agreement with the resilient modulus is possible if larger values of dynamic deviator stress are chosen, but the choice is arbitrary and any amount of agreement could be obtained by an appropriate choice of value for the dynamic deviator stress.

NUMERICAL VALUES OF THE ALLOWABLE LOAD-CARRYING CAPACITY AND REQUIRED OVERLAY THICKNESS

For a validation of the procedures outlined in this study, a number of rigid and flexible pavement structures at the three selected airport sites were evaluated for single- and multiple-wheel loadings, and the allowable load-carrying capacity and the required overlay thickness were the results of nondestructive testing and layered elastic theory. For these pavement structures, the allowable load-carrying capacity and the required overlay thickness were also determined by the conventional CBR and DSM methods for AC pavements and by the Westergaard and DSM methods for rigid pavements. Tables 4-12 and Figures 19-22 show the results.

In Tables 4-12, the allowable load is expressed in terms of total gross aircraft load and the load on one wheel of each aircraft. Figure 19 presents comparisons of the allowable load on a single wheel with contact area of 254 sq in. This contact area corresponds to the contact area of the 18-in.-diam load plate of the 16-kip vibrator. Figure 20 makes similar comparisons for the allowable gross load of a DC-8 aircraft.

Figures 23 and 24 show the effect of varying the elastic properties of the pavement layers on the resulting allowable load in the layered elastic theory. These figures give the preliminary results of a sensitivity study for AC pavements, which shows the dependence of the predicted allowable load-carrying capacity on the values of the Young's

Table 4. Allowable Load and Required Overlay Thickness (Layered-Elastic Theory), Albuquerque Sunport

Site	Feature	Sta	Pavement Type	Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.*				PCC Required Overlay Thickness, in.*			
				SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 17-35	6+13	PCC	80	147	261	269	38	35	31	32	0	5	7	9	0	2.0	3.0	4.0
2	R/W 17-35	19+00	AC	84	147	294	336	40	35	35	40	0	2.0	2.0	3.0	--	--	--	--
3	R/W 17-35	100+07	PCC	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
4	North warmup	Apron	PCC	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
5	T-1	7+00	AC	147	252	505	589	70	60	60	70	0	0	0	0	--	--	--	--
6	T-1	21+00	AC	137	232	463	547	65	55	55	15	0	0	0	0	--	--	--	--
7	T-3D	2+00	AC	74	126	253	295	35	30	30	35	0	4	5	5	--	--	--	--
8	R/W 3-21	9+00	AC	44	88	177	202	21	19	19	23	4	7	8	8	--	--	--	--
9	R/W 12-30	1+05	PCC	38	67	118	118	18	16	14	14	10	14	15	16	6	9	10	10
10	R/W 12-30	30+00	AC	143	253	488	573	68	60	58	68	0	0	0	0	--	--	--	--
11	T-2	9+00	AC	72	135	253	303	34	30	30	36	0	3	4	4	--	--	--	--
12	T-2	56+00	AC	48	88	177	202	23	21	21	24	4	6	8	7	--	--	--	--
13	T-2	48+00	AC	93	168	320	370	44	40	40	44	0	1	1.5	1.5	--	--	--	--
14	T-6	4+12.5	PCC	156	253	488	573	74	60	58	68	0	0	0	0	0	0	0	0
15	T-3B	2+00	AC	76	135	269	303	36	32	32	36	0	3	3	4	--	--	--	--
16	T-8	21+00	AC	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
17	T-8	87+00	AC	137	253	505	589	65	60	60	70	0	0	0	0	--	--	--	--

* Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

Table 5. Allowable Load and Required Overlay Thickness (CBR Method), Albuquerque Sunport

Site	Feature	Sta	Pavement Type	CBR/k	Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.*			
					SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 17-35	6+13	PCC	20 305 k	89	130	304	390	42	31	36	46	--	--	--	--
2	R/W 17-35	19+00	AC	54	284	424	738	884	135	101	88	105	0	0	0	0
3	R/W 17-35	101+07	PCC	13 235 k	36	56	146	178	17	13	17	21	--	--	--	--
4	North warmup	--	PCC	25 340 k	43	73	73	187	20	17	22	27	--	--	--	--
5	T-1	7+00	AC	20	183	271	446	540	87	64	53	64	0	0	0	0
6	T-1	21+00	AC	25	228	339	558	675	108	81	66	80	0	0	0	0
7	T-3D	2+00	AC	38	215	321	553	659	102	76	66	78	0	0	0	0
8	R/W 3-21	9+00	AC	18	102	153	259	309	48	36	31	37	0	0.8	3.5	2.3
9	R/W 12-30	1+05	PCC	14 250 k	41	66	172	207	20	16	20	25	--	--	--	--
10	R/W 12-30	30+00	AC	54	574	838	1351	1663	273	199	160	197	0	0	0	0
11	T-2	9+00	AC	26	124	191	335	400	59	45	40	48	0	0	0.7	0.5
12	T-2	56+00	AC	15	79	118	205	245	38	28	24	29	0	2.6	5.5	4.2
13	T-2	48+00	AC	16	140	209	336	399	67	50	40	47	0	0	2.0	1.4
14	T-6	4+12.5	PCC	35 325 k	170	233	472	603	81	55	56	72	--	--	--	--
15	T-3B	2+00	AC	55	276	420	733	876	131	100	87	104	0	0	0	0
16	T-8	21+00	AC	41	312	473	795	935	148	112	94	111	0	0	0	0
17	T-8	87+00	AC	48	436	649	1067	1290	207	154	127	153	0	0	0	0

* Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

Table 6. Allowable Load and Required Overlay Thickness (DSM Method), Albuquerque Support

Site	Feature	Sta	Pavement Type	DSM	Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.*				PCC Required Overlay Thickness, in.*			
					SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 17-35	6+13	PCC	2008	75	102	217	291	36	24	26	35	0	7	6	9	0	9	8	10
2	R/W 17-35	19+00	AC	850**	78	116	202	246	37	28	24	29	0	2.5	4	4	--	--	--	--
3	R/W 17-35	100+07	PCC	615	23	36	89	111	11	9	11	13	--	--	--	--	--	--	--	--
4	North warmup	Apron	PCC	1486	56	81	186	249	27	19	22	30	0	6	4	8	3	8	7	9
5	T-1	7+00	AC	880**	81	116	183	226	38	28	22	27	0	4	8	7	--	--	--	--
6	T-1	21+00	AC	812**	75	107	169	197	35	26	20	23	0	4	10	8	--	--	--	--
7	T-3D	2+00	AC	685**	60	88	151	186	28	21	18	22	0.8	5	9	7	--	--	--	--
8	R/W 3-21	9+00	AC	509**	45	66	114	139	21	16	14	16	3	8	12	11	--	--	--	--
9	R/W 12-30	1+05	PCC	930	35	57	140	171	17	14	17	20	7	12	9	15	8	11	9	13
10	R/W 12-30	30+00	AC	1010**	96	137	215	262	46	33	26	31	0	3	7	6	--	--	--	--
11	T-2	9+00	AC	751**	69	104	179	222	33	25	21	26	0	3	7	5	--	--	--	--
12	T-2	56+00	AC	667**	25	87	150	183	25	21	18	22	1.7	5	9	7	--	--	--	--
13	T-2	48+00	AC	720**	62	91	146	169	29	22	17	20	0.9	6	12	11	--	--	--	--
14	T-6	4+12.5	PCC	4175	156	205	353	464	74	49	42	55	0	0	0	0	0	0	0	0
15	T-3B	2+00	AC	678**	60	90	150	178	29	21	18	21	0.8	5	8	7	--	--	--	--
16	T-8	21+00	AC	809**	74	108	172	204	35	26	20	24	0	4	9	7	--	--	--	--
17	T-8	87+00	AC	938**	86	127	207	238	41	30	25	28	0	3	8	6	--	--	--	--

* Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

** DSM values have been adjusted for temperature on AC pavement

Table 7. Allowable Load and Required Overlay Thickness (Layered-Elastic Theory), Knox County Airport, Rockland, Maine

				Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.*			
Site	Feature	Sta	Pavement Type	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 21	3+00	AC	65	109	202	244	31	26	24	29	2	6	9	8
2	R/W 21	23+00	AC	36	63	135	152	17	15	16	18	5	7	7	8
3	R/W 21	37+00	AC	36	67	135	152	17	16	16	18	5	7	8	8
4	T-B	22+00	AC	25	46	93	109	12	11	11	13	7	11	14	13
5	Ramp	15+00A	AC	13	23	46	55	6	5.5	5.5	6.5	12	17	22	22
6	R/W 13	42+00	AC	--	--	--	--	--	--	--	--	--	--	--	--
7	R/W 13	30+00	AC	65	109	202	236	31	26	24	28	2	6	9	8
8	R/W 13	2+65	AC	78	139	269	312	37	33	32	37	0	3	3	3
9	T-A	6+00	AC	--	--	--	--	--	--	--	--	--	--	--	--

* Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

Table 8. Allowable Load and Required Overlay Thickness (CBR Method*), Knox County Airport, Rockland, Maine

Site	Feature	Sta	Pavement Type	Pavement Thickness	Base CBR	Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.**			
						SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 3-21	3+00	AC	3.5	43	56	91	156	196	27	22	19	23	1	4	6	5
2	R/W 3-21	23+00	AC	3.25	35	43	68	120	151	20	16	14	18	3	6	8	7
3	R/W 3-21	37+00	AC	3.0	52	61	97	166	211	29	23	20	25	1	3	5	4
4	T-B	22+00	AC	3.25	40	49	78	137	172	23	19	16	20	2	5	7	5
5	Ramp	15+00	AC	3.25	43	53	84	147	185	25	20	17	22	2	4	6	5
6	R/W 13-31	42+00	AC	4.375	34	54	87	151	188	14	12	10	12	2	5	7	5
7	R/W 13-31	30+00	AC	4.0	37	54	87	153	189	26	21	18	22	2	5	7	5
8	R/W 13-31	2+65	AC	3.0	10	12	19	32	41	6	5	4	5	14	20	27	24
9	T-A	6+00	AC	3.5	39	51	82	141	177	24	19	17	21	2	5	7	6

* Used only over base CBR's to get allowable load and used multi program

** Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

Table 9. Allowable Load and Required Overlay Thickness (DSM Method), Knox County Airport, Rockland, Maine

Site	Feature	Sta	Pavement Type	DSM	Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.*			
					SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 3-21	3+00	AC	549	49	68	103	118	23	16	12	14	3	12	20	20
2	R/W 3-21	23+00	AC	583	52	70	110	127	25	17	13	15	3	11	19	20
3	R/W 3-21	37+00	AC	615	55	67	94	118	26	16	11	14	8	19	34	41
4	T-B	22+00	AC	500	44	51	76	92	21	12	9	11	10	24	40	46
5	Ramp	15+00	AC	381	35	42	59	73	17	10	7	9	16	29	48	54
6	R/W 13-31	42+00	AC	746	69	87	129	158	33	21	15	19	4	12	18	21
7	R/W 13-31	30+00	AC	482	41	57	89	100	19	14	11	12	5	14	22	23
8	R/W 13-31	2+65	AC	600	54	65	107	127	26	15	13	15	3	15	22	24
9	T-A	6+00	AC	671	60	76	111	135	29	18	13	16	5	14	25	26

* Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

Table 10. Allowable Load and Required Overlay Thickness (Layered-Elastic Theory), Minneapolis-St. Paul International Airport

Site	Feature	Sta	Pavement Type	Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.*				PCC Required Overlay Thickness, in.*			
				SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 11L-29R	5+65	PCC	126	185	371	472	60	44	44	56	0	0	0	0	0	0	0	0
2	R/W 11L-29R	49+95	PCC	114	173	362	455	54	41	43	54	0	0	0	0	0	0	0	0
3	R/W 11R-29L	7+15	AC/PCC	257	417	935	1103	122	99	111	131	0	0	0	0	0	0	0	0
4	R/W 11R-29L	78+30	AC/PCC	269	392	817	1044	128	93	97	124	0	0	0	0	0	0	0	0
5	R/W 4R-22L	4+35	PCC	112	168	354	446	53	40	42	53	0	1.0	1.0	0	0	0	0	0
6	R/W 4R-22L	62+47	PCC	200	316	704	859	95	75	84	102	0	0	0	0	0	0	0	0
7	T 11L-29A	3+00	PCC	196	320	716	851	93	76	85	101	0	0	0	0	0	0	0	0
8	T 11R-29L	4+75	PCC	164	257	573	707	78	61	68	84	0	0	0	0	0	0	0	0
9	T 4R-22L	1+70	PCC	103	152	303	379	49	36	36	45	0	3.5	5.0	4.0	0	1.5	2.0	1.5
10	New reserve taxiway	7+34	PCC	213	299	564	716	101	71	71	85	0	0	0	0	0	0	0	0
11	East side taxiway	12+45	PCC	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
12	Old north ramp	12+45	PCC	116	181	396	488	55	43	47	58	0	0	0	0	0	0	0	0
13	Old ramp	12+45	AC/PCC	42	67	143	177	20	16	17	21	6.0	11.0	12.0	12.0	5.0	9.0	9.0	9.0
14	Ramp	12+45	PCC	131	181	328	413	60	43	39	49	0	0	3.5	2.0	0	0	1.5	1.0

* Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

Table 11. Allowable Load and Required Overlay Thickness (DSM Method), Minneapolis-St. Paul International Airport

Site	Feature	Sta	Pavement Type	Total Allowable Load, kips					Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.*				PCC Required Overlay Thickness, in.*			
				DSM	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 11L-29R	5+65	PCC	3150	118	171	384	522	56	41	46	62	0	0	0	0	0	4	2	0
2	R/W 11L-29R	49+95	PCC	2648	99	143	322	439	47	34	38	52	0	0	0	0	0	6	5	2
3	R/W 11R-29L	7+31	AC/PCC	3435**	128	174	354	475	61	41	42	56	0	0	0	0	0	0	0	0
4	R/W 11R-29L	78+30	AC/PCC	5754**	215	282	516	688	102	67	61	82	0	0	0	0	0	0	0	0
5	R/W 4R-22L	4+35	PCC	1835	69	96	217	288	33	23	26	34	0	3	3	0	1	7	7	4
6	R/W 4R-22L	62+47	PCC	4740	177	241	545	729	84	57	65	87	0	0	0	0	0	4	2	0
7	T 11L-29R	3+00	PCC	3880	145	204	452	617	69	48	54	73	0	0	0	0	0	4	2	0
8	T 11R-29L	4+75	PCC	6700	250	351	784	1065	119	83	93	126	0	0	0	0	0	4	2	0
9	T 4R-22L	1+70	PCC	1840	69	97	215	293	33	23	26	35	0	0	0	0	0	5	4	1.6
10	New reserve taxiway	7+34	PCC	2955	110	150	310	419	52	36	37	50	0	0	0	0	0	0	0	0
11	East side taxiway	13+70	PCC	7760	290	400	866	1153	138	95	103	140	0	0	0	0	0	0	0	0
12	Old north ramp		PCC	1720	64	89	192	256	30	21	23	30	0	8	8	5	3	9	9	7
13	Old ramp		AC/PCC	904**	34	46	92	124	16	11	11	15	0	6	7	3	0	7	8	5
14	Terminal apron		PCC	5420	203	275	559	760	96	65	66	90	0	0	0	0	0	4	3	0

* Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

** Temperature corrected DSM

Table 12. Allowable Load and Required Overlay Thickness (Westergaard Method), Minneapolis-St. Paul International Airport

Site	Feature	Sta	Pavement Type	k*	Total Allowable Load, kips				Allowable Load on One Wheel, kips				AC Required Overlay Thickness, in.**				PCC Required Overlay Thickness, in.**			
					SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10	SW	BOE-727	DC-8	DC-10
1	R/W 11L-29R	5+65	PCC	450	128	190	450	579	61	45	53	69	0	0	0	0	0	4	3	0
2	R/W 11L-29R	49+95	PCC	360	108	161	389	498	51	38	46	59	0	0	0	0	0	6	5	2
3	R/W 11R-29L	7+31	AC/PCC	260	165	235	517	665	78	56	61	79	0	0	0	0	0	2	1	0
4	R/W 11R-24L	78+30	AC/PCC	435	245	345	740	954	116	82	88	113	0	0	0	0	0	0	0	0
5	R/W 4R-22L	4+35	PCC	230	99	143	333	428	46	34	40	51	0	3	3	0	1	7	7	4
6	R/W 4R-22L	62+47	PCC	500	145	211	490	588	69	50	58	70	0	0	0	0	0	3	1	0
7	T 11L-29R	3+00	PCC	350	131	192	453	583	62	46	54	69	0	0	0	0	0	4	3	0
8	T 11R-29L	4+75	PCC	540	137	203	483	622	65	48	57	74	0	0	0	0	0	4	2	0
9	T 4R-22L	1+70	PCC	270	111	163	384	494	53	39	46	59	0	0	0	0	0	6	4	3
10	New reserve taxiway	7+34	PCC	500	212	304	674	866	101	72	80	103	0	0	0	0	0	0	0	0
11	East side taxiway	13+70	PCC	450	185	265	596	766	88	63	71	91	0	0	0	0	0	0	0	0
12	Old north ramp		PCC	155	87	125	281	360	41	30	33	43	0	8	8	5	3	9	9	7
13	Old ramp		AC/PCC	105	39	61	158	195	19	15	19	23	0	6	7	3	0	7	8	5
14	Terminal apron		PCC	220	139	195	419	538	66	46	50	64	0	0	0	0	0	4	4	0

* k values determined from CBR (small aperture test)

** Loads on one wheel:
SW (35,625 lb)
BOE-727 (41,090 lb)
DC-8-63F (42,510 lb)
DC-10-10 (51,420 lb)

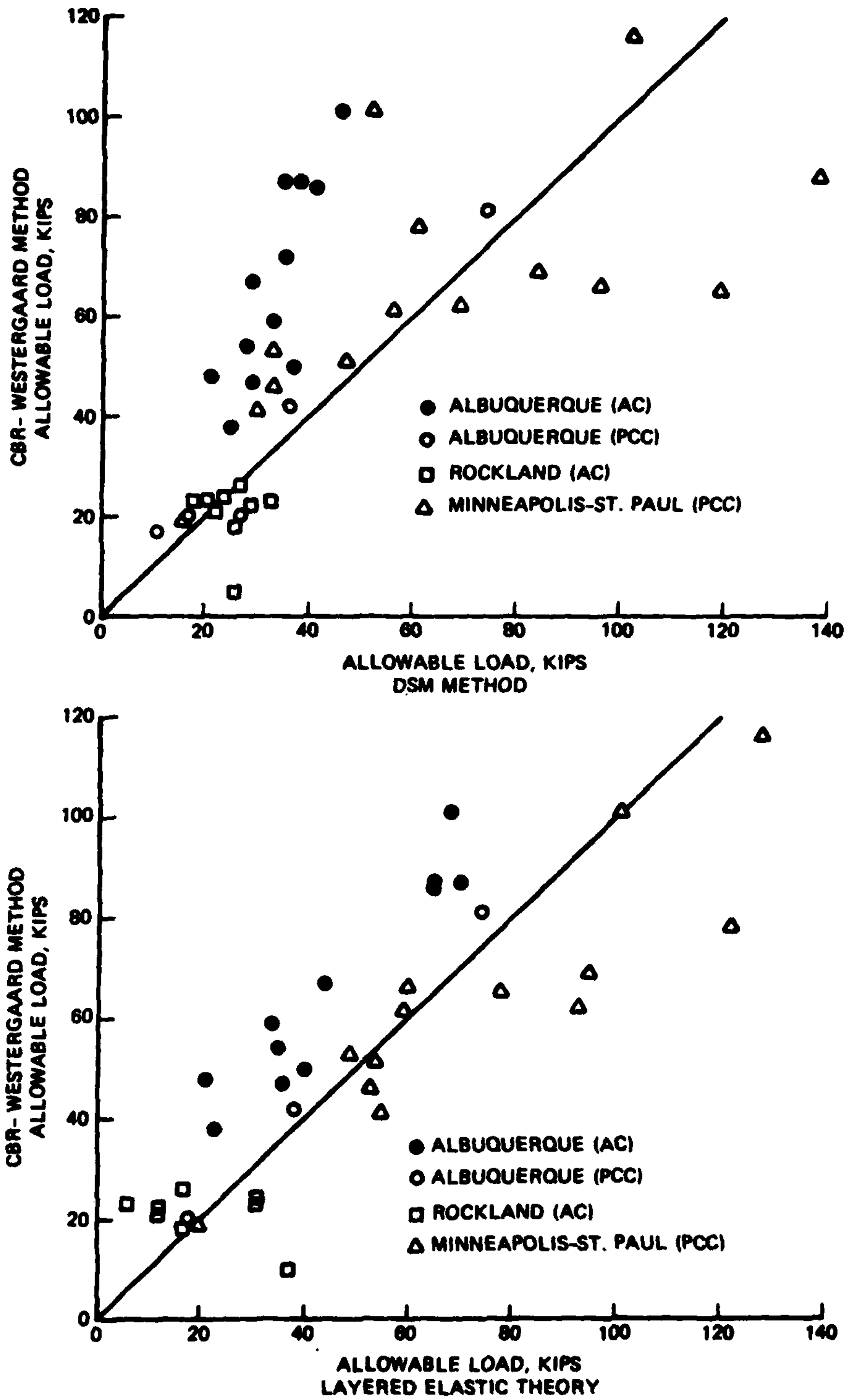


Figure 19. Comparisons of allowable load on single wheel by PAVEVAL, DSM, and CBR methods

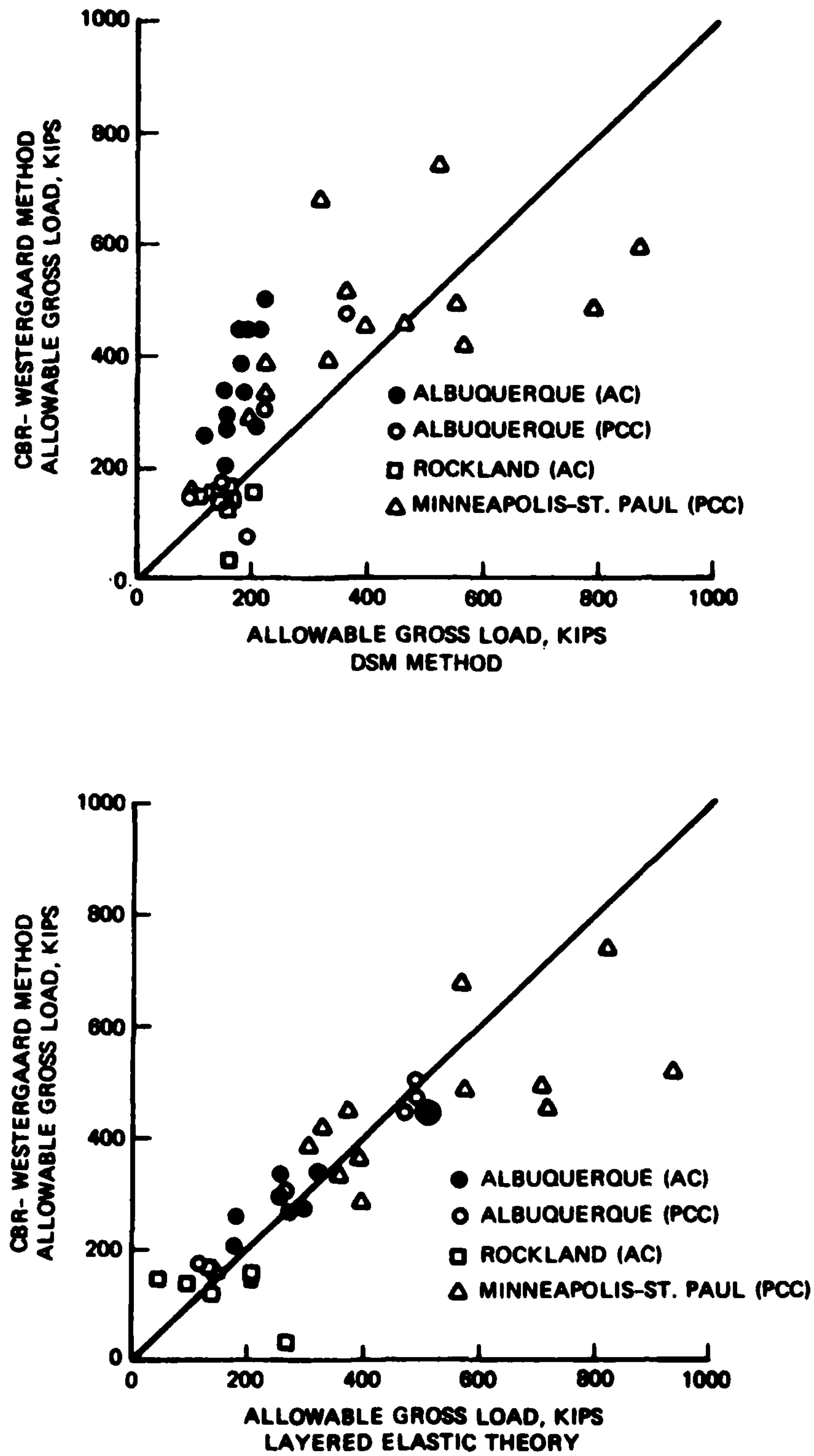
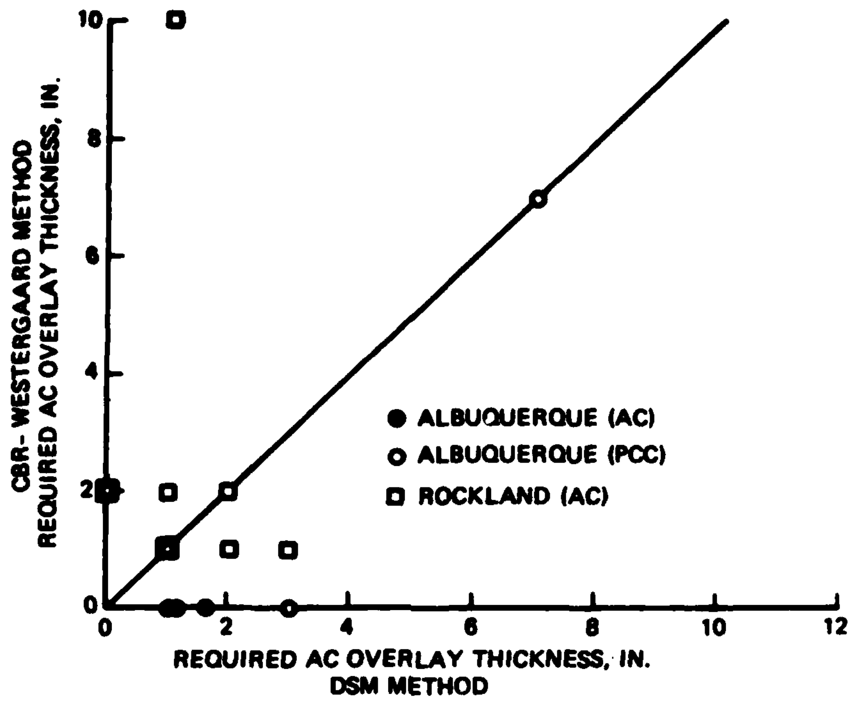


Figure 20. Comparison of allowable gross load on DC-8 aircraft by PAVEVAL, DSM, and CBR methods



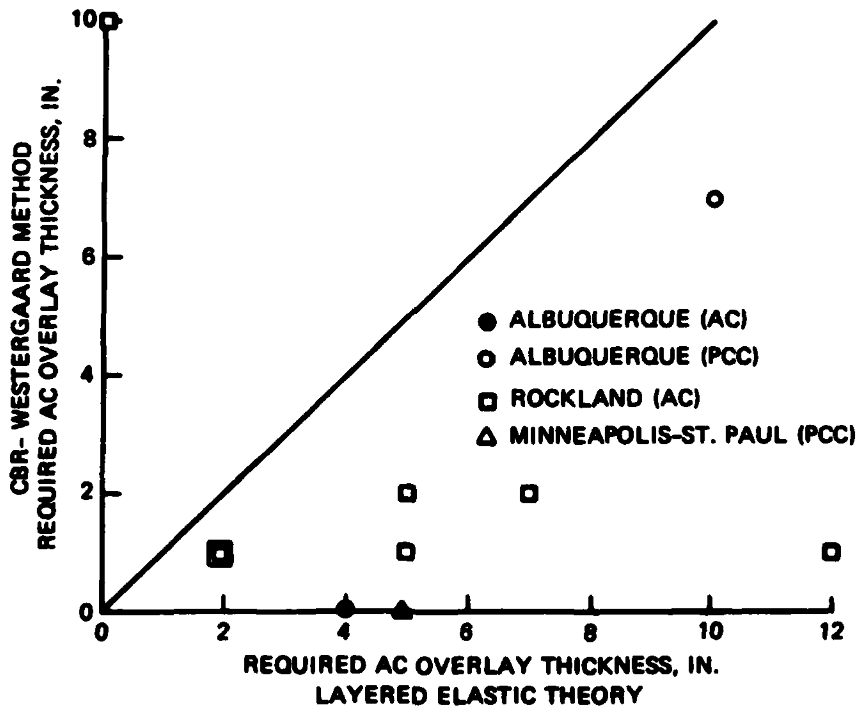
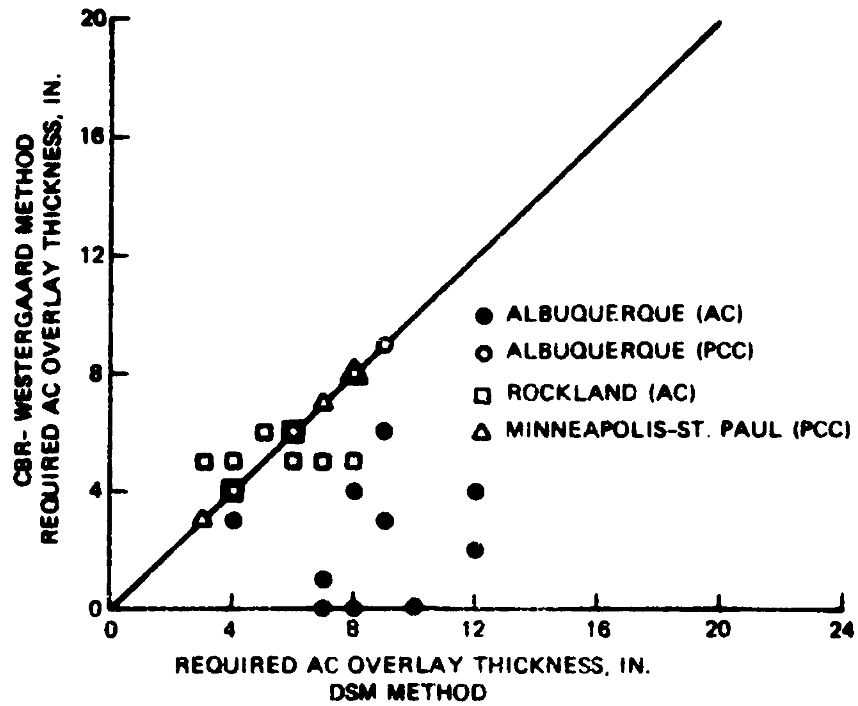


Figure 21. Comparisons of required overlay thickness for single wheel by PAVEVAL, DSM, and CBR methods



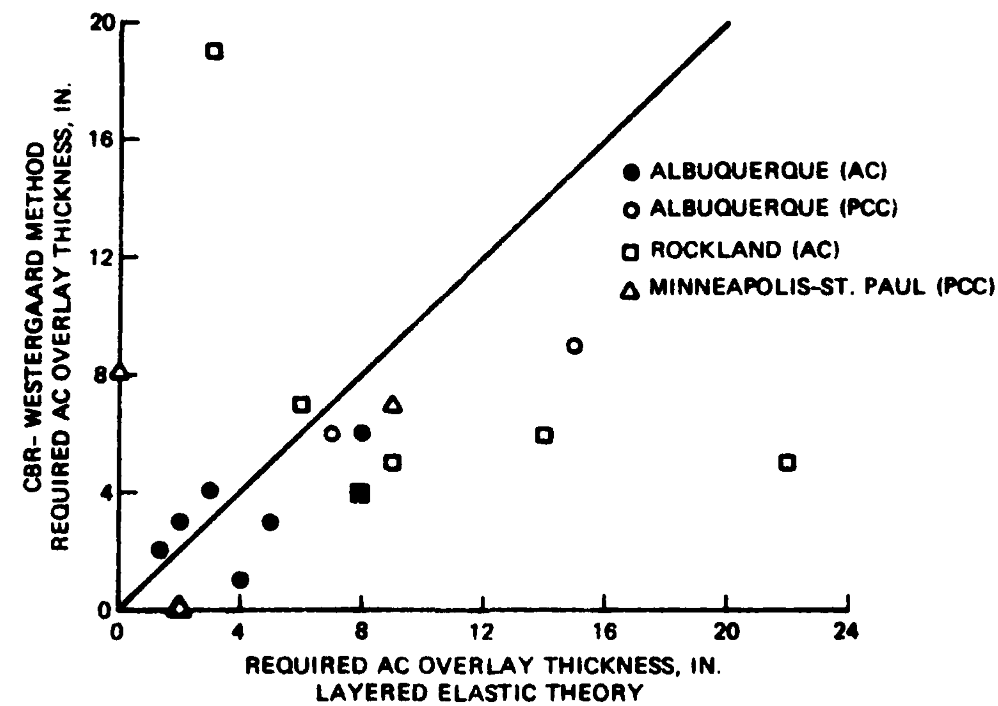


Figure 22. Comparisons of required overlay thickness for DC-8 aircraft by PAVEVAL, DSM, and CBR methods

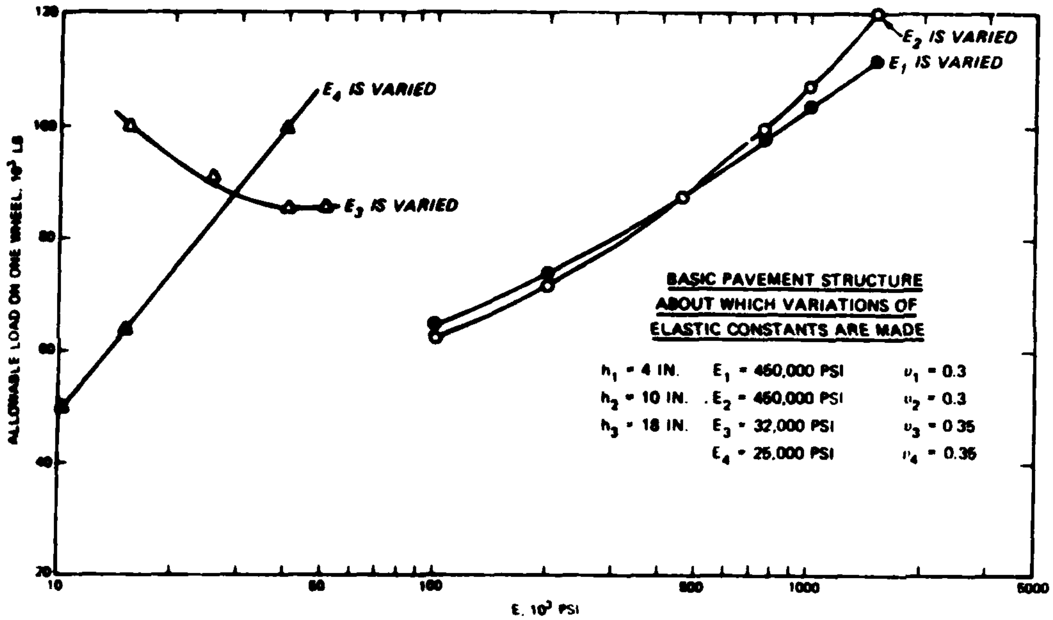


Figure 23. Sensitivity study of allowable load for AC pavement (case of strong base)

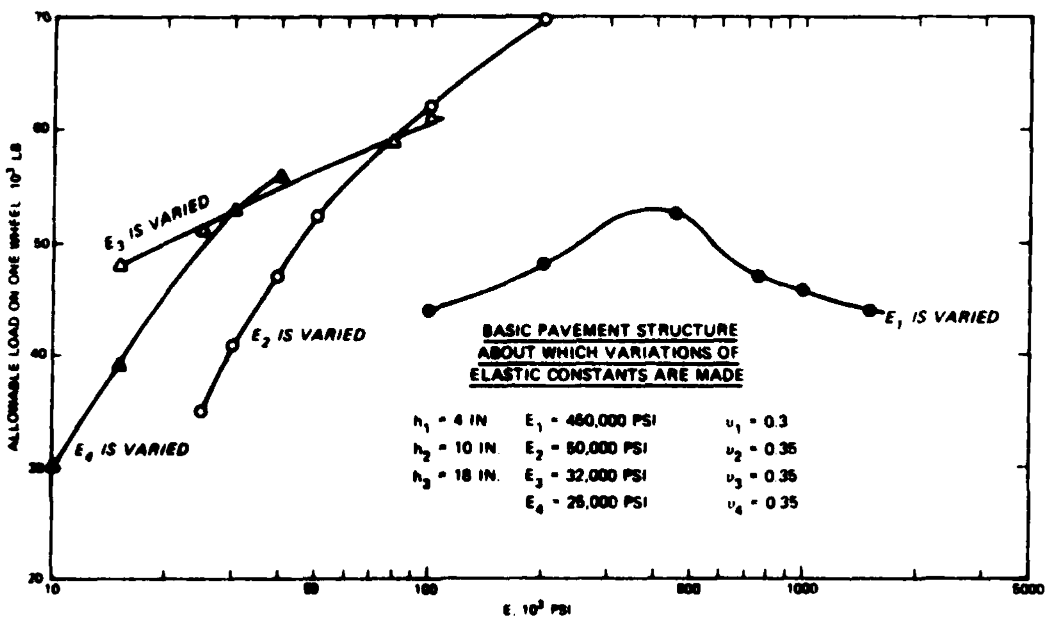


Figure 24. Sensitivity study of allowable load for AC pavements (case of weak base)

moduli of the pavement layers. The layered elastic theory approach to pavement evaluation predicts a very complicated dependence of the allowable load on the layered elastic structure of the pavement. Figure 23 shows the results for the case of an AC layer over a relatively strong base layer, while Figure 24 illustrates the results for the case of an AC layer over a relatively weak base layer. The results for these two cases are quite different because the limiting vertical strain in the subgrade is manifested for the case of a strong base, while the limiting tensile strain at the bottom of the AC layer tends to control for the case of an AC layer over a relatively weak base.

The results of Figures 23 and 24 indicate that the layered elastic theory and the prescribed limiting strain and stress conditions produce a predicted allowable load-carrying capacity that is very sensitive to the elastic properties of the pavement. In particular, under some conditions the predicted allowable load may be a decreasing function of the Young's moduli of the pavement layers. This is due in some cases to the fact that the limiting tensile strain at the bottom of the AC layer is a decreasing function of the AC Young's modulus.[14,18] For instance, in Figure 24 the allowable load increases with the AC Young's modulus up to a point where the decrease in the value of the limiting tensile strain at the bottom of the AC layer begins to lower the allowable load.

SUMMARY AND CONCLUSIONS

SUMMARY

The capability of determining the load-carrying capacity of a pavement and the overlay thickness required to upgrade a pavement is of much importance to pavement engineers. A simple method of pavement evaluation combining vibratory nondestructive field tests with a theoretical layered elastic formalism was developed to satisfy the needs of the pavement engineer.[7] The pavement evaluation and overlay design is based on the subgrade Young's modulus value determined from vibratory nondestructive testing and the subgrade Young's modulus value used in a layered elastic theory computer program to calculate the allowable load-carrying capacity and the required overlay thickness of a pavement.

Two computer programs, SUBE and PAVEVAL, are used to evaluate a pavement based on the combined layered elastic theory and vibratory nondestructive test approach. The computer program SUBE predicts the value of the subgrade Young's modulus from the measured dynamic load-deflection curves and the known values of the elastic moduli and thicknesses of the pavement layers. The computer program PAVEVAL calculates the allowable load-carrying capacity and the required overlay thickness based on the layered elastic theory by relating the limiting stress and strain values at points in the pavement or subgrade to the magnitude of the static load applied to the pavement surface.

The validation of the results of the combined predictions of the computer programs SUBE and PAVEVAL was obtained at three airport sites and included AC and PCC pavements.

CONCLUSIONS

The theoretical and experimental work done for the validation of the procedure of using the combined methods of vibratory nondestructive testing and layered elastic theory for calculating the allowable load-carrying capacity and the required overlay thickness of a pavement yielded the following conclusions:

_a_. For the sites considered, generally poor agreement is obtained between the values of the subgrade Young's modulus predicted by the computer program SUBE and the formula $E_s = 1500$ CBR, and by extraction of the Young's modulus from the laboratory resilient modulus measurements.

_b_. Although there is some scattering of data in comparing allowable loads from PAVEVAL with the standard CBR method, there is generally good agreement. As a matter of fact, the agreement between the PAVEVAL results and the CBR method is better than between the DSM method and the CBR method. The greatest scatter occurred with the AC pavements at Albuquerque and some PCC pavements at Minneapolis-St. Paul.

_c_. Results from the overlay comparisons were not as encouraging as the allowable load comparisons. The PAVEVAL analysis tended to predict thicker overlays than did the CBR method.

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